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SPECTROPHOTOMETER-BASED COLOR MEASUREMENTS

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14. ABSTRACT
This report presents a study to evaluate the practical feasibility of using a spectrometer outfitted with an integrating sphere for the quantitative measurement of color. The precision of the measurement was evaluated and found to be very high. The accuracy was evaluated using nominal values for L*a*b* (color space) from international paint suppliers. The results demonstrate the value of using a spectrophotometer for color measurements. The experimental L*a*b* values for a large number of colors from the federal color standard listing are reported.

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CONTENTS

TABLES

SUMMARY

This report presents a study to evaluate the practical feasibility of using a spectrometer outfitted with an integrating sphere for the quantitative measurement of color. Measurements were done on a large number of certified federal color standard swatches and some actual fire control equipment. The instrument and method precision were evaluated, and compared to the needed precision, to distinguish samples with adjacent federal color standard identification numbers. The color measurement results from two different instruments on a small set of samples were evaluated. The values of color parameters from federal color samples were compared with values from international sources for the determination of method accuracy. The experimental results for L*a*b* values for a large number of federal color standards were also reported. The results demonstrate the value of using a spectrophotometer for color measurements.

INTRODUCTION

Color is an important specification for equipment used by the U.S. military. The need for improved color measurements in the U.S. military has been recognized for many years (ref. 1). The U.S. Government issues a set of official color standards to be used by all government agencies. The last set of standards was issued in 2008 (ref. 2). Traditional approaches within the U.S. military for color testing are based on visual inspection. There are several problems with this approach. Visual inspection of color is quite subjective; two different testers can get quite different results. Secondly, visual color inspection is quite dependent upon the lighting and illumination conditions. Consequently, visual color inspection in northern New Jersey may not be relevant to conditions in the Middle East. Therefore, it is important that improved methods of color testing be used on a regular basis.

Color testing by spectrophotometers is scientifically well-accepted (ref. 3). Spectrometers are used for color measurements in many industries including the paint industry. Spectrometers can provide rapid, highly reproducible, and accurate color measurements of military equipment. There are several American Society for Testing and Materials (ASTM) chapters covering the use of spectrometers for color measurements (refs. 3 and 4). The Department of Defense has officially accepted these chapters for use by the U.S. military. However, the practical acceptance of these newer approaches has been slow. A previous Army Research Laboratory (ARL), Adelphi, MD, study of federal standard colors was done before the release of the latest version of federal color standards in 2007; therefore, many newer official federal color standards are not well documented. Furthermore, most of the data from the ARL study was published in 1989. The purpose of this study is to evaluate the feasibility of spectrometer-based color measurements for fire control equipment and to establish possible specification requirements for color values based on the actual precision of the spectrometer-based color measurement.

METHODS, ASSUMPTIONS, AND PROCEDURES

A set of federal standard color swatches was purchased from FED-STD.com. The color swatches were handled with care. Reference color values were obtained from several sources including international color standard suppliers*.

*The website www.e-paint.co.uk has L*a*b* values for federal standard colors, but they are only nominal values.

Most of the measurements conducted in this report were done with a Perkin Elmer Lambda 1050 dual beam spectrophotometer outfitted with a 150-mm diameter integrating sphere to measure diffuse reflection. The dual beam spectrometer allows for subtraction of lamp intensity noise from the measurement, leading to highly accurate absorbance values. On a daily basis, the instrument was allowed to warm up for 45 min to 1 hr before operation. In addition, a daily internal check of the wavelength accuracy of the instrument was done using internal lamp spectral lines.

A 99% reflectance standard from Labsphere Inc., North Sutton, NH, was used as a diffuse reflectance standard before every set of measurements. The reflection spectra were collected from 380 to 780 nm at 10-nm intervals. The spectra were converted to reflection values using the Perkin Elmer software. The experimental values were calculated from these spectra using the Perkin Elmer software and procedures described in ASTM chapter E308 (ref. 3). All spectral data was stored on the computer. A summary of the color calculations is found in appendix A. There are many different methods for color evaluation based on different illumination conditions. For this study, the D_{65} illumination standard was used to determine color parameters because the D_{65} standard is designed to simulate conditions of bright outdoor natural lighting.

Studies using the Perkin Elmer spectrometer were also done to evaluate instrument and method precision. Because it is critical to estimate the variation in color measurement between different instruments, measurements were also done on selected federal color standard samples using a second instrument, a Photo Research spectroradiometer model 715. The second setup used a tungsten lamp and a 1-m diameter integrating sphere. No effort was made to standardize the two instruments. It is expected that standardization of the instruments would significantly reduce the variation between the two instruments. These systematic measurements of method accuracy and precision allow for the establishment of color specification limits based on scientific data and not guesswork.

For simplicity in this report, the L* a* and b* values are used with D_{65} illumination to describe color. The L*a*b* values can often be described in a three-dimensional graph as shown in figure 1. The L* value shows the lightness or darkness of the sample, a* is in the amount of magenta versus green, and b* is the amount of yellow versus green. The L*a*b* values also have the advantage over the x, y, z tristimulus values used to describe color because they more uniformly span the visible color space.

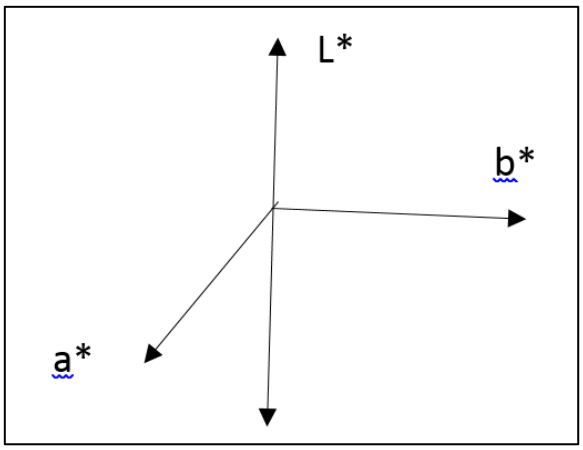

Figure 1
L*a*b* diagram

There are many possible metrics to express the similarity, or lack thereof, between two colors (ref. 5). In this report, the Euclidean distance metric, ΔE, is used and recommended in ASTM D2244. The equation given is:

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

The ΔE in equation 1 is a Euclidean distance in the L*a*b* space between the two color measurements. Geometrically, this is the distance between the tips of the two vectors in L*a*b* space. The ΔE parameter allows both the accuracy and precision of color measurements to be quantified. The accuracy is the distance between the experimental values and the actual reference color values. The precision is the average distance between the average measurement and a set of individual measurements. Therefore, a set of very precise color measurements on the same sample will lie very close to each other in the L*a*b* space.

RESULTS AND DISCUSSION

The instrument precision was evaluated by measuring the same color standard (no. 34084) six times. Six data points were chosen because it is more than enough data to estimate the variation within the data. Typical results are shown in table 1. It can be seen that the instrument precision (or reproducibility) is very high. The ΔE value was found to be 0.53. Similar instrument precision results are found for other colors.

Table 1
Instrument precision

		L*	a*	b*
34090-1	Green	39.04	-33.85	11.28
34090-2	Green	39.04	-33.87	11.3
34090-3	Green	39.04	-33.86	11.29
34090-4	Green	39.04	-33.87	11.3
34090-5	Green	38.71	-32.89	11.03
34090-6	Green	38.71	-32.89	11.03
	avg	38.88	-33.38	11.16
	var	0.03	0.24	0.02
	ΔE	0.53		

The method precision was evaluated by using the measurements shown in this report. A selected sample, a piece of black foam, was placed in the spectrometer and measured. The sample was then removed, and then placed back in the sample holder, and the measurement was done. This was repeated a total of six times. A second and third operator (labeled A, B, and C) repeated the experimental procedure in order to evaluate the method for operator variation. The results of these measurements are reported in table 2. As expected, the color values from the spectrophotometer are very reproducible. It is reasonable to conclude that the instrument precision

and the operator to operator variation is very small, with a ΔE of less than one. The ΔE in equation 1 is a Euclidean distance in the L*a*b* space between the two color measurements.

Table 2
Method precision and operator variability

		Color Parameters		
		L	a	b
Operator	A	29.12	-0.19	-1.92
		29.1	-0.2	-1.92
		29.03	-0.19	-1.87
		28.96	-0.18	-1.84
		29.07	-0.22	-1.9
		28.95	-0.18	-1.83
	B	28.95	-0.2	-1.88
		28.98	-0.2	-1.87
		29	-0.19	-1.88
		28.97	-0.21	-1.86
		29.02	-0.2	-1.88
		29.04	-0.2	-1.85
	C	29.1	-0.2	-1.94
		29.1	-0.21	-1.94
		29.11	-0.21	-1.93
		29.08	-0.19	-1.89
		29.11	-0.21	-1.93
		29.08	-0.2	-1.94

It is of practical importance to determine if the spectrometer can distinguish between two similar colors or colors that are next to each other on the federal standard list. In many product descriptions, color tolerance values are described in this or a similar manner. The data in table 3 describes such an experiment. Federal standard color nos. 34084 and 34086 were each measured three times. The results clearly demonstrate that the two colors can easily be distinguished using the spectrometer. The ΔE value for the two colors was found to be $\Delta E = 7.57$. This is much larger than the method precision that, as noted in an earlier section, was found to be less than one.

Table 3
Comparison of two similar colors

sample #	L	a	b
34084	28.4	-0.32	3.74
34084	28.41	-0.33	3.76
34084	28.41	-0.31	3.76
34086	35.7	-1.29	5.58
34086	35.69	-1.27	5.55
34086	35.69	-1.28	5.55

A comparison of quantitative color values for 10 samples from two different instruments is shown in table 4. Values were obtained using a Perkin Elmer spectrophotometer and a Photo Research, Inc., New York, NY, spectral radiometer. The results are clearly quite compatible, but as expected, the errors are larger than the instrument precision. The average ΔE was found to be 4.9. Smaller values would be obtained if the two instruments were standardized, that is made to be similar by using a mathematical transformation of the data from one of the instruments. This number is important because it is representative of the variation to be expected in color measurements from different laboratories at different facilities with different equipment.

Table 4
Comparison of color values from two instruments

			Photo Research Radiometer				Perkin Elmer				
Fed Std 595 Number	name		L	a	b		L	a	b		ΔE
30145	butternut stain		42.3711	6.3045	16.4835		44.59	6.94	18.77		3.25
31350	red		40.9485	47.0277	26.1441		42.27	53.64	30.86		8.23
32555	orange		69.8014	18.5825	44.7244		73.45	21.07	49.54		6.53
33814	yellow		81.1359	-11.1801	28.7994		85.47	-11.67	31.38		5.07
34090	green		36.8455	-29.256	9.5246		39.4	-33.85	11.28		5.54
35183	blue		44.2834	-3.0149	-31.7029		46.74	-5.76	-33.43		4.07
36231	aircraft gray #23		51.6411	-1.2299	-2.1828		54.45	-1.61	-2.14		2.83
37030	black camo		22.7763	0.7361	-0.9478		23.13	0.04	-0.74		0.81
37875	aircraft white		86.1562	-2.6007	5.2387		91.09	-2.79	5.55		4.95
										average	4.59

The color values for 10 colors are shown in table 5. Some of these U.S. Army colors are from the most recent set of federal color standards and do not have reported X, Y, and Z chromaticity values. Comparison of the L* a* and b* values for federal standard colors listed in tables 5 and 6 yielded very good results. The variation between these results and the published values for the standards was calculated using equation 1 for ΔE.

Table 5
Ten color standards compared with nominal reference values

			Reference				Experimental		
Fed Std 595 Number	NAME		L	a	b		L	a	b
30145	butternut stain		43.98	8.15	17.81		44.59	6.94	18.77
31350	red		41.54	48.19	27.59		42.27	53.64	30.86
32555	orange		72.05	23.29	46.6		73.45	21.07	49.54
33814	yellow		84.83	-7.64	30.3		85.47	-11.67	31.38
34090	green		39.24	-31.11	12.15		39.4	-33.85	11.28
35183	blue		48.87	-12.25	-30.23		46.74	-5.76	-33.43
36231	aircraft gray #23		54.95	-1.63	-2.16		54.45	-1.61	-2.14
37030	black camo		23.14	-0.19	-0.74		23.13	0.04	-0.74
37875	aircraft white		90.67	-2.4	5.44		91.09	-2.79	5.55

Table 6
Summary of estimated method accuracy ΔE values comparing the experimental values with reference values

Fed Std 595 Number	name			ΔE
30145	butternut stain			1.66
31350	red			6.40
32555	orange			3.94
33814	yellow			4.22
34090	green			2.88
35183	blue			7.54
36231	aircraft gray #23			0.50
37030	black camo			0.23
37875	aircraft white			0.58
			average	3.11

Appendix B lists the L*a*b* values for a large number of federal standard colors. The L*a*b* values are listed only for D65 illumination. This study focused on the federal color standards with numbers 30,000 and above because these are low gloss colors that are most common in U.S. Army and other military applications. It was found the values for L* a* and b* compared quite favorably with values from international sources (footnote). A histogram of ΔE values for over 200 samples is shown in figure 2. The average ΔE value was found to be 2.5. No outliers were removed from the data set. For completeness, C_{ab} and h_{ab} values are also shown for each sample in appendix B. The C_{ab} is the modulus of the a*b* vector, and h_{ab} is the angle in the a*b* plane. The formulas for C_{ab} and h_{ab} are given in appendix A.

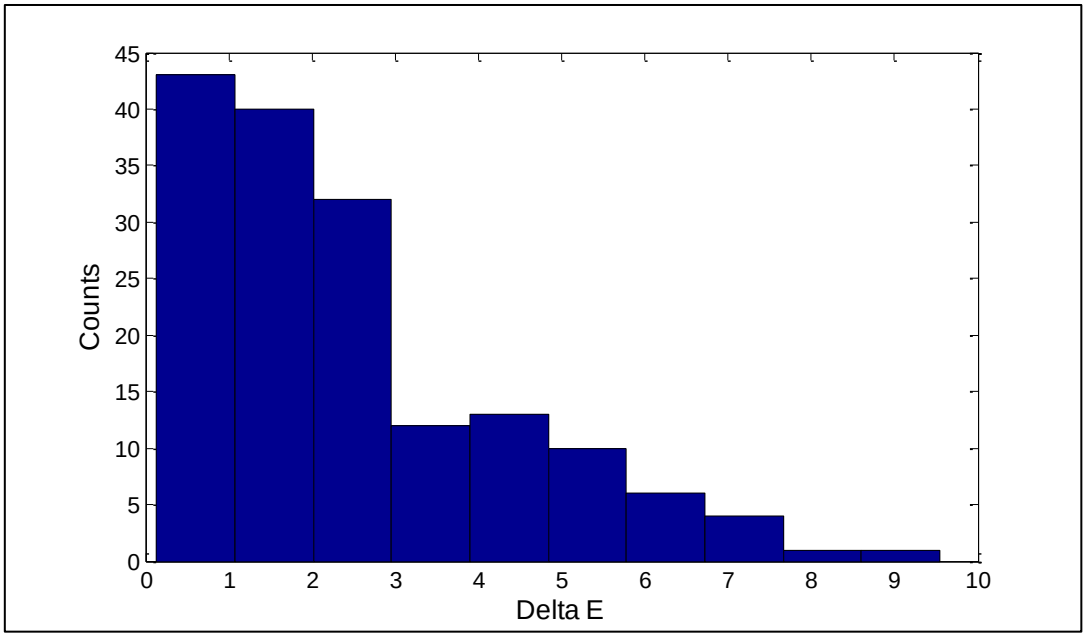

Figure 2
Distribution of ΔE values for over 200 federal color standards

Color measurements using the Perkin Elmer instrument were made on a laser rangefinder from an unspecified vendor. The laser rangefinder was mounted with a chemical ring stand clamp in front of the integrating sphere. The use of an integrating sphere makes such measurements possible because it is able to collect light over a region about 1 in. in diameter. The experimental values, L*= 39.3, a* =2.63, and b* =15.68, are consistent with federal standard color no. 30118, field drab camouflage.

CONCLUSIONS

The feasibility of performing color measurements using a spectrometer outfitted with an integrating sphere was investigated. The study strongly suggests that a spectrometer is a good experimental approach for the measurement of color. The spectrometer provides a very high degree of precision so that small color differences can be measured with considerable precision. The instrument and method precision were found to be very good with $\Delta E \leq 1.0$. The instrument to instrument variation was larger than the method precision for a single instrument, but this is expected when no attempt was made to standardize the two spectral measurements. The accuracy of the method was quite good, and an average ΔE of 2.5 was found using a set of over 200 colors from the federal standard color list. Because the reference values used in this accuracy determination were not certified values, it is possible that error in the reference values measurably contributed to the observed ΔE value. It is proposed that the best way to verify the color of a unit under test is to compare the unit color with a federal color standard swatch using the same instrument because this approach negates the issue of instrument to instrument variability and allows for the detection of small ΔE values, i.e., changes in color.

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4. “Standard Practice for Visual Appraisal of Colors and Color Differences of Diffusely-Illuminated Opaque Materials,” ASTM D1729, American Society for Testing and Materials (ASTM), 2009.

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APPENDIX A
CALCULATION OF COLOR PARAMETERS FROM SPECTRAL DATA

In this Appendix A we outline the calculation of the color parameters given spectral data. Color calculations are based on diffuse reflection measurements over the spectral range of 380 to 780 nm. The spectra were collected in 10 nm increments. Before the color calculations can be done, the illumination conditions must be selected, i. e. A, C, or D_{65}. The angle of observation must also be selected, typically 2 or 10 degrees are options. Since D65 is designed to simulate daylight conditions, we have chosen to show our results using that set of illumination conditions. A 2 degree angle of illumination was used for all calculations in this paper. The first calculation is to determine X, Y, and Z, the tristimulus values. In general the tristimulus values are given by

$$X = k\sum R(\lambda)S(\lambda)\bar{x}(\lambda)\Delta\lambda$$

$$Y = k\sum R(\lambda)S(\lambda)\bar{y}(\lambda)\Delta\lambda$$

$$Z = k\sum R(\lambda)S(\lambda)\bar{z}(\lambda)\Delta\lambda$$

Where k is a normalization constant, R(λ) is the reflectivity as a function of wavelength, S(λ) is the strength of the selected illumination, and x(λ) is the basis function for the X tristimulus value. Tables for S and the basis functions x, y, and z are in ASTM chapter E308. For a perfect reflector, k is chosen to set the three tristiumlus values to 100. The L*, a*, and b* values are calculated from X, Y, Z and the corresponding X_n, Y_n, and Z_n values. The X_n, Y_n, and Z_n values are also called white point values and their numerical values for different illumination conditions is given in tables in ASTM chapter E308. The equations used to calculate L*, a*, b* are given below.

$$L^* = 116f(Q_Y) - 16$$

$$a^* = 500[f(Q_X) - f(Q_Y)]$$

$$b^* = 200[f(Q_Y) - f(Q_Z)]$$

where $Q_X = \left({}^{X}/_{X_n}\right)\ Q_Y = \left({}^{Y}/_{Y_n}\right)\ Q_Z = \left({}^{Z}/_{Z_n}\right)$

and $f(Q_i) = Q_i^{1/3}\ if\ Q_i > \left(\frac{6}{29}\right)^3$

else $\left({}^{841}/_{108}\right) Q_i + {}^{4}/_{29}\ if\ Q_i \leq \left(\frac{6}{29}\right)^3$

i varies as X, Y, and Z

The purpose of the L*, a*, b* values is to make the color space more uniform. The L*, a*, b* values uniquely define the color of an object.

APPENDIX B
TABLE OF L*A*B* VALUES FOR FEDERAL COLOR STANDARDS

Fed Std Number	Description	D_{65} , 2 degree illumination				
		L*	a*	b*	Cab*	Hab*
10055	DOT Brown	36.85	9.2	12.28	15.34	53.17
11086	DOT Red-1	40.38	45.15	21.56	50.03	25.53
11105	DOT Red-2	40.44	46.36	20.77	50.8	24.14
11105	OSHA Red-1	40.48	46.41	20.82	50.87	24.17
11120	OSHA Red-2	45.16	45.91	21.87	50.86	25.47
11140	OSHA Red-3	40.87	45.06	21.4	49.88	25.4
12197	OSHA Int'l Orange	50.68	41.69	31.83	52.45	37.36
12243	DOT Orange	58.06	36.16	46.5	58.9	52.13
12246	OSHA Orange-1	55.99	42.84	40.7	59.09	43.53
12300	OSHA Orange-2	63.49	32.1	56.91	65.34	60.58
13415	DOT SBY	70.53	20.09	62.83	65.96	72.27
13507	DOT Yellow-1	77.04	17.04	72.35	74.33	76.74
13538	DOT Yellow-2	73.22	17.84	70.74	72.96	75.85
13591	OSHA Yellow-1	81.99	-1.51	72.37	72.38	91.2
13655	OSHA Yellow-2	79.51	9.78	78.97	79.58	82.94
14066	DOT Green-1	34.93	-20.57	3.4	20.85	170.62
14109	DOT Green-2	37.12	-22.41	5.11	22.98	167.15
14120	OSHA Green-1	45.88	-36.83	5.79	37.28	171.06
14260	OSHA Green-2	59.5	-25.86	9.53	27.56	159.78
15065	DOT Blue-1	36.52	-3.16	-27.05	27.24	263.34
15090	DOT Blue-2	35.81	-5.21	-23.11	23.69	257.28
15092	OSHA Blue-1	45.75	-7.27	-32.49	33.3	257.4
15102	OSHA Blue-2	40.83	-2.46	-28.38	28.49	265.04
17142	OSHA Purple-1	46.46	31.83	-11.03	33.69	340.89
17155	OSHA Purple-2	47.81	29.24	-16.1	33.38	331.17
20065	Brown 356	37.76	2.61	6.01	6.55	66.5
20065	Brown 356	37.78	2.58	6.04	6.57	66.85
20122	Brown	40.58	8.35	13.74	16.08	58.7
20150	Coyote 476/498	45.85	3.81	15.44	15.9	76.14
20170	Olive Mohave	49.44	3.56	13.78	14.24	75.51
20180	Tan 499	51.93	0.43	12.97	12.97	88.08
20220	Light Coyote 481	54.72	3.96	14.13	14.68	74.35
20233	Brown	54.63	15.86	13.52	20.84	40.45
20270	Urban Tan 478	61.82	3.91	9.72	10.48	68.07
20372	Tan	66.75	2.1	12.25	12.43	80.26
20460	Sample 1	75	0.08	11.95	11.95	89.6
20475	Sample 2	74.57	5.28	21.51	22.15	76.22
21158	Red	50.4	40.97	12.82	42.93	17.38
Fed Std Number	**Description**	**D_{65} , 2 degree illumination**				

		L*	a*	b*	Cab*	Hab*
23430	Khaki P1	61.3	0.23	15.23	15.23	89.12
23525	Desert Sand 500/503	74	0.99	9.7	9.75	84.19
23530	Light Tan 479	69.22	2.57	9.57	9.9	74.99
23594	Beige	81	4.4	37.44	37.7	83.3
23793	Yellow	89.17	-7.29	42.54	43.16	99.72
24070	Army Green 491	34.45	-3.34	0.96	3.47	163.95
24108	Dark Green	41.34	-14.11	5.33	15.09	159.3
24112	Green 474	40.23	-6.73	3.56	7.62	152.15
24165	Foliage Green 502/504	46.69	-3.13	2.48	3.99	141.65
24190	Sample 3	58.58	-43.77	27.76	51.83	147.62
24226	Green	56.58	-7.89	6.41	10.16	140.88
24417	Green	71.07	-7.97	9.67	12.53	129.5
24552	Seafoam Green	78.7	-10.26	31.99	33.6	107.79
25102	Light blue	40.99	-1.67	-28.73	28.78	266.68
26099	Sample 4	40.92	-1.57	-4.13	4.42	249.18
26118	Sample 5/Medium gunship gray	41.72	-0.37	-5.42	5.44	266.1
26255	Dark Gray 509	55.5	-0.65	-2.27	2.36	253.93
26290	Gray 26270	59.74	-1.2	-0.86	1.47	215.77
27041	Black	28.41	0.49	-1.87	1.94	284.75
27855	White 506	88.85	-2.07	19.3	19.41	96.13
30040	Brown	31.2	2.69	5.15	5.81	62.37
30045	Brown 045	32.76	6.68	5.52	8.67	39.58
30051	Brown Camo	33.84	4.34	6.86	8.11	57.68
30059	Brown 059	27.62	8.04	8.81	11.93	47.61
30097	Earth Brown Camo	35.29	3.9	11.26	11.91	70.9
30099	Earth Brown	38.34	3.96	11.11	11.79	70.4
30108	Walnut Brown/Red Brown	31.85	6.31	9.25	11.2	55.71
30109	Dull Red	39.01	22.82	16.34	28.07	35.59
30111	Maroon olympic russet	36.47	14.23	10.59	17.74	36.65
30117	Earth Red/International Brown	42.71	11.57	15.66	19.47	53.55
30118	Field drab camoulage	40.3	2.86	18.26	18.48	81.09
30145	Butternut Stain (1)	44.59	6.94	18.77	20.01	69.71
30145	Butternut Stain (2)	44.59	6.95	18.77	20.01	69.68
30145	Butternut Stain (3)	44.58	6.94	18.76	20	69.71
30145	Butternut Stain (4)	44.59	6.94	18.77	20.01	69.71
Fed Std Number	**Description**	**D_{65} , 2 degree illumination**				
		L*	**a***	**b***	**Cab***	**Hab***
30160	Maroon	35.37	23.98	3.73	24.27	8.85
30166	Burgundy	39.72	21.89	15.71	26.94	35.66

30206	Light Maroon	50.11	13.46	8.63	15.99	32.65
30215	Brown	47.79	12.82	24.44	27.6	62.32
30219	Bark	51.38	7.91	16.13	17.97	63.87
30227	Light Tan	55.41	7.62	13.3	15.33	60.17
30233	Blush	51.53	17.19	15.59	23.21	42.21
30252	Light Blush	55.54	20.73	23	30.97	47.97
30257	Coyote Brown	61.63	10.29	32.9	34.47	72.64
30266	Mud Brown	57.13	6.18	31	31.61	78.73
30277	Brown	58.58	1.37	16.39	16.45	85.22
30279	Brown	62.67	7.51	14.18	16.05	62.09
30313	Brown	62.04	8.23	12.45	14.93	56.53
30315	Brown	63.02	6.96	13.54	15.22	62.81
30318	Brown	63.41	1.67	16.69	16.77	84.28
30324	Pink	61.47	7.33	13.83	15.65	62.08
30372	Tan	64.76	2.12	13.54	13.7	81.1
30450	Beige	71.25	6.13	15.85	16.99	68.86
30475	Mocha	71.82	5.56	22.19	22.88	75.94
31090	Mud	39.74	11.22	21.05	23.85	61.93
31136	Int'l/CARC Aircraft - Red	38.51	36.13	18.95	40.8	27.68
31158	Light Int'l Red	49.07	41.67	13.92	43.94	18.48
31302	Red	46.99	49.76	31.08	58.67	31.99
31310	Red	46.84	51.63	37.03	63.54	35.65
31350	Red (1)	42.27	53.64	30.86	61.88	29.92
31350	Red (2)	42.27	53.64	30.87	61.89	29.92
31350	Red (3)	42.27	53.63	30.85	61.87	29.91
31350	Red (4)	42.26	53.63	30.85	61.87	29.91
31400	Red	49.34	46.15	32.04	56.18	34.77
31400	Red	49.39	46.2	32.15	56.28	34.83
31433	Blush	65.28	17.09	17.8	24.68	46.17
31575	Light Blush	75.6	11.59	16.83	20.43	55.44
31638	Beige	75.53	22.58	7.81	23.9	19.09
31643	Beige	82.94	6.11	17.14	18.2	70.38
31668	Flesh	84	9.34	9.45	13.29	45.31
32169	Candy Red	46.93	28.48	33.06	43.64	49.26
32246	Red Apple	55.36	45.56	46	64.74	45.27
Fed Std Number	**Description**	**D_{65} , 2 degree illumination**				
		L*	**a***	**b***	**Cab***	**Hab***
32555	Orange (1)	73.45	21.07	49.54	53.83	66.95
32555	Orange (2)	73.44	21.07	49.54	53.84	66.96
32555	Orange (3)	73.43	21.09	49.53	53.83	66.94
32555	Orange (4)	73.43	21.07	49.55	53.84	66.96
32630	Flesh 0	79.04	8.73	21.14	22.87	67.55

32648	Flesh 8	79.13	8.7	25.16	26.62	70.93
33070	Coffee	33.6	-1.45	11.97	12.06	96.91
33105	Brown	40.65	3.33	19.13	19.42	80.12
33245	Beige 45	55.68	9.28	29.87	31.28	72.74
33275	Beige 75	59.13	11.76	53.43	54.71	77.59
33303	Green 03	60.82	0.3	17.78	17.79	89.03
33434	Beige 34	68.4	10.38	48.69	49.79	77.96
33440	Brown 440	56.61	2.81	26.93	27.07	84.04
33446	Beige 446	66.6	3.74	19.71	20.06	79.24
33448	Dark Tan	67.72	3.03	23.64	23.83	82.68
33481	Cream	70.65	-2.14	52.28	52.32	92.35
33510	Eggshell	71.49	1.57	17.5	17.57	84.88
33522	Rose	73.9	1.7	17.18	17.26	84.36
33531	Beige	75.04	2.75	14.57	14.82	79.32
33538	Orange 538	74.94	18.25	74.83	77.02	76.29
33564	Beige 564	80.36	-0.82	23.05	23.06	92.04
33578	Beige 578	80.07	0.49	21.03	21.03	88.67
33613	Flesh 613	82.87	6	24.09	24.82	76.01
33617	Tan 617	78.72	1.75	17.14	17.23	84.18
33637	Orange	71.85	8.35	69.99	70.49	83.19
33655	Orange	78.35	9.92	82.75	83.34	83.16
33685	Yellow	85.91	-7.09	28.35	29.22	104.04
33690	Peach	83.29	0.79	19.54	19.56	87.7
33695	Orange	83.07	2.93	43.47	43.57	86.14
33696	Tan 696	84.86	5.31	56.5	56.75	84.63
33711	Tan 711	83.55	2.89	22.71	22.89	82.76
33717	Beige 717	85.62	0.8	20.73	20.75	87.78
33722	Beige 722	84.46	0.08	24.75	24.75	89.82
33793	Yellow	89.23	-6.02	42.37	42.79	98.09
33798	Yellow	88.44	-1.72	35.25	35.29	92.79
33814	Yellow (1)	85.47	-11.67	31.38	33.48	110.41
33814	Yellow (2)	85.48	-11.68	31.39	33.49	110.41
33814	Yellow (3)	85.47	-11.66	31.37	33.47	110.39
Fed Std Number	**Description**	**D_{65} , 2 degree illumination**				
		L*	**a***	**b***	**Cab***	**Hab***
33814	Yellow (4)	85.47	-11.68	31.39	33.49	110.42
34031	Black	30.07	-0.38	2.73	2.75	97.88
34052	Grey	32.85	-2.54	3.22	4.1	128.34
34058	Green	32.06	-12.25	-3.64	12.78	196.56
34064	Dark Green	31.61	-2.04	5.56	5.92	110.15
34079	Forest Green	36.03	-3.84	7.85	8.74	116.03
34082	Green 82	38.19	-8.15	13.91	16.12	120.38

34083	Black 83	31.11	-4.49	8.84	9.91	116.96
34084	Gray 84	28.51	-0.32	3.69	3.7	94.95
34086	Black 086	35.75	-1.25	5.48	5.62	102.8
34088	Green 088	40.65	-1.1	12.34	12.39	95.1
34089	Green 089	40	-8.06	23.19	24.55	109.17
34090	Green (1)	39.04	-33.85	11.28	35.68	161.56
34090	Green (2)	39.04	-33.87	11.3	35.71	161.56
34090	Green (3)	39.04	-33.86	11.29	35.7	161.56
34090	Green (4)	39.04	-33.87	11.3	35.7	161.55
34090	Green (5)	38.71	-32.89	11.03	34.69	161.46
34090	Green (6)	38.71	-32.89	11.03	34.69	161.47
34090	Green (7)	38.72	-32.9	11.04	34.71	161.45
34090	Green (8)	38.72	-32.89	11.04	34.7	161.45
34092	Forest Green 092	35.98	-8.74	2.22	9.01	165.75
34094	Green 383 CAMO	35.1	-6.63	9.17	11.32	125.87
34095	Green 095	34.89	-7.63	13.03	15.1	120.36
34096	Foliage Green	35.96	-4.37	8.94	9.95	116.04
34097	Foliage Green 2	40.71	-9.62	14.15	17.11	124.21
34098	Olive Drab 98	40.99	-5.58	18.33	19.16	106.92
34102	OD Green	38.16	-7.59	13.08	15.12	120.12
34108	Aqua Green	40.09	-17.07	6.48	18.25	159.21
34127	Military Green 127	39.71	-5.68	18.28	19.14	107.26
34128	Military Green 128	41.88	-11.16	9.93	14.94	138.33
34130	Military Green 130	38.14	-6.18	18.36	19.37	108.6
34138	Military Green 138	46.49	-24.45	21.95	32.86	138.09
34148	Military Green 148	45.21	-9.41	-2.8	9.82	196.59
34158	ACU Gray	45.68	-6.39	-0.54	6.41	184.81
34159	Woodland Camo	47.33	-6.33	5.66	8.49	138.24
34226	Gray Green	54.64	-8.3	6.62	10.61	141.42
34227	Weeds Green	55.71	-14.29	13.58	19.72	136.46
34230	Lime Green	54.55	-38.11	28.6	47.65	143.12
Fed Std Number	**Description**	**D_{65} , 2 degree illumination**				
		L*	**a***	**b***	**Cab***	**Hab***
34227	Weeds Green	55.71	-14.29	13.58	19.72	136.46
34230	Lime Green	54.55	-38.11	28.6	47.65	143.12
34233	Gray	57.71	-7.74	-0.41	7.75	183.05
34241	Aircraft Gray	61.39	-13.58	3.46	14.01	165.69
34258	Green	53.72	-9.63	22.28	24.27	113.38
34259	Army Green	49.17	-5.42	37.06	37.45	98.33
34272	OD Green 72	58.24	-21.56	12.14	24.74	150.62
34277	Gray 77	59.48	-9.88	2.46	10.18	166.04
34300	Slate	61.63	-13	4.87	13.88	159.47

34325	Lime Green	64.86	-18.22	3.99	18.66	167.65
34373	Rust	67.14	-11.59	10.51	15.64	137.8
34410	Gray 410	69.25	-9.83	5.64	11.33	150.18
34414	Gray 414	73.62	-9.82	9.8	13.87	135.06
34424	Sand 424	70.03	-6.36	12.07	13.64	117.8
34432	Tan 432	69.74	-7.16	8.24	10.92	130.99
34441	BeigeTan 441	70.51	-10.27	12.72	16.35	128.92
34449	Charcoal	71.87	-13.86	13.2	19.13	136.4
34491	Marshmallow	73.09	-13.02	8.36	15.47	147.29
34504	Gray	72.25	-10.96	10.81	15.39	135.4
34516	Gray 16	76.01	-9.88	7.04	12.14	144.52
34518	Air Force Gray	72.45	-10.15	7.64	12.71	143.03
34524	OD Green 524	74.34	-12.56	20.48	24.02	121.52
34533	OD Green 533	72.54	-13.36	18.26	22.62	126.19
34540	Light K Green 540	75.32	-33.27	30.28	44.98	137.7
34552	OD Green 552	77.52	-10.17	33.21	34.73	107.02
34554	Flesh 554	81.33	-6.05	14.9	16.08	112.09
34558	Cream	78.92	-12.14	13.16	17.91	132.7
34583	Root Beer	73.27	-7.7	15.13	16.98	116.96
34666	Lemon	85.89	-17.13	28.82	33.52	120.72
34670	Rock Brown	83.49	-7.88	7.33	10.76	137.1
34672	Peach	82.54	-8.91	13.46	16.14	123.5
35042	Black 042	28.57	-1.07	-4.19	4.32	255.64
35044	Black Blue 044	24.82	4.37	-8.83	9.85	296.31
35045	Drk Blue 045	27.37	-1.5	8.25	8.39	259.68
35048	Navy Blue 048	27.4	3.6	-17.15	17.52	281.86
35056	Navy Blue 56	27.62	10.48	-26.51	28.5	291.56
35095	Royal Blue 95	38.24	7.94	-40.07	40.85	281.21
35109	Flat Blue	42.17	-5.94	-15.59	16.68	249.15
Fed Std Number	**Description**	**D_{65} , 2 degree illumination**				
		L*	**a***	**b***	**Cab***	**Hab***
35164	Blue Gray	46.6	-2.8	-9.34	9.75	253.33
35177	Ant Blue	48.09	-6.03	-16.61	17.67	250.05
35180	Sky Blue	42.44	-0.17	-37.6	37.6	269.73
35183	Blue (1)	46.74	-5.76	-33.43	33.92	260.23
35183	Blue (2)	46.74	-5.75	-33.45	33.94	260.24
35183	Blue (3)	46.74	-5.75	-33.45	33.94	260.24
35183	Blue (4)	46.74	-5.76	-33.43	33.93	260.23
35183	Blue (5)	46.61	-3.69	-33.67	33.87	263.74
35183	Blue (6)	46.62	-3.7	-33.66	33.86	263.73
35183	Blue (7)	46.61	-3.69	-33.66	33.86	263.74
35183	Blue (8)	46.61	-3.69	-33.66	33.87	263.74

35189	Brown Gray	53.94	-6.43	-6.7	9.28	226.17
35190	Slate Blue	54.44	-9.83	-16.45	19.17	239.14
35193	Table Gray	51.57	-15.42	-10.3	18.55	213.73
35231	Violet	54.79	1.12	-23.51	23.54	272.73
35237	Airplane Gray 237	55.33	-3.86	-4.83	6.18	231.35
35240	Violet 240	57.76	-1.45	-21.68	21.73	266.18
35250	Light Blue 250	60.89	-10.57	-31.78	33.49	251.6
35275	Aqua Green 275	58.4	-28.82	-13.89	31.99	205.73
35299	Gray 299	61.77	-18.58	-2.39	18.73	187.34
35352	Light Gray	61.53	-10.27	-1.5	10.38	188.29
35414	Medium Gray	64.4	-11.28	-2.62	11.58	193.08
35450	Light Purple	68.87	-8.31	-16.12	18.13	242.73
35466	Ceramic	74.27	-18.25	-18.61	26.07	225.55
35488	Blue Violet	71.91	-5.58	-15.92	16.87	250.7
35526	Gray 526	73.57	-7.05	-4.71	8.48	213.78
35550	Sand 550	84.36	-5.86	-3.15	6.66	208.25
35622	Tan 622	82.31	-5.86	3.02	6.59	152.76
35630	Light Beige 630	83.87	-1.71	4.23	4.57	111.99
36076	Dark Blue 076	33.94	0.34	-5.49	5.5	273.55
36081	Dark Gray Blue	37.54	-1.24	-0.43	1.31	198.98
36099	Black Gray	37.78	-2.37	-4.72	5.28	243.35
36118	Slate Gray 18	40.45	-0.45	-5.41	5.43	265.23
36152	Brown 152	45.58	-2.09	-2.59	3.32	231.14
36173	Slate Gray 73	49.46	-1.64	-4.72	5	250.83
36231	Aircraft gray #23 (1)	54.45	-1.61	-2.14	2.67	233.05
36251	Gray 251	55.1	-1.27	-0.35	1.32	195.2
36270	Aircraft Gray 270	56.8	-1.51	-2.17	2.64	235.2
Fed Std Number	**Description**	**D_{65} , 2 degree illumination**				
		L*	**a***	**b***	**Cab***	**Hab***
36280	Gray 280	58.11	-1.99	0.74	2.12	159.63
36293	Seagull Gray 293	58.54	-1.85	-1.6	2.45	220.89
36300	Gray 300	62.18	-0.85	-4.49	4.57	259.24
36306	Brown 306	59.65	1.73	6.61	6.83	75.38
36307	Brown 307	62.11	-2.63	4.45	5.17	120.53
36314	Tan 314	60.97	-3.13	1.04	3.3	161.63
36320	Gray 320	60.78	-2.26	-5.64	6.08	248.21
36357	Tan 57	64.34	-1.94	7.44	7.69	104.58
36373	Gray 73	65.84	-2.63	-0.87	2.77	198.3
36375	Desert 75	66.53	-1.49	-4.89	5.11	253.02
36405	Hedgehog	73.84	-1.49	13.16	13.24	96.47
36415	Sand	71.06	1.62	15.69	15.78	84.12
36424	Flesh 424	73.38	0.92	7.57	7.62	83.09

36440	Light Gray 440	70.43	-1.87	5.48	5.79	108.88
36463	Seagull Gray 463	68.76	-1.63	-0.22	1.64	187.78
36473	Gray 473	67.85	-4.74	-0.44	4.76	185.34
36492	Sand Gray 492	75.5	-1.67	3.48	3.86	115.64
36495	Ship Gray 495	80.18	-2.32	-0.08	2.32	182.07
36521	Light Beige 521	75.05	1.49	9.46	9.58	81.08
36555	Tan 555	77.38	-1.12	16.42	16.45	93.91
36559	Light Beige 559	76.89	-2.39	8.7	9.02	105.34
36586	Light Beige 586	77.98	-1.74	14.07	14.18	97.06
36595	Headstone Gray 595	77.92	-3.32	8	8.66	112.54
36622	Tan 622	77.79	-2.08	6.85	7.16	106.92
36628	Lighter Gray 628	82.21	-2.42	3.11	3.94	127.85
36642	Flesh 642	83.67	3.7	14	14.48	75.19
37030	Black camo (1)	23.13	0.04	-0.74	0.74	273.03
37030	Black camo (2)	23.14	0.03	-0.72	0.72	272.44
37030	Black camo (4)	23.14	0.05	-0.73	0.73	273.82
37031	Flat Black 031	22.63	-0.04	-0.76	0.76	267.11
37038	Black 38	23.12	0.04	-0.55	0.55	274.11
37056	Magenta	30.13	2.48	2.96	3.86	50.06
37100	Purple	34.5	24.7	-18.86	31.08	322.64
37142	Pink	43.75	36.03	-12.17	38.03	341.33
37144	Pink 144	45.68	20.1	-14.92	25.03	323.43
37150	Tan 150	81.28	0.07	8.41	8.41	89.52
37200	Beige 200	64.39	-0.37	-0.35	0.51	223.36
37722	Light Tan 722	85.15	-1.35	8.69	8.8	98.85
Fed Std Number	**Description**	**D_{65} , 2 degree illumination**				
		L*	**a***	**b***	**Cab***	**Hab***
37769	Flesh 769	85.7	-0.37	13.3	13.31	91.6
37778	Light Flesh 778	89.22	-1.83	13.21	13.33	97.91
37855	Flesh 855	88.75	-1.55	19.76	19.82	94.49
37886	Yellow 886	92.49	-1.44	9.39	9.5	98.74
37925	White 925	94.77	-1.84	4.68	5.03	111.44

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Spectrometer Based Color Measurements
Title / Project

Frederick H. Torg, Ph.D.
Author/Project Engineer

Report number/Date received (to be completed by LCSD)

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David Magidson
Division Chief (Date)

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LCSD 49 (1 Sept 16)
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