NIST Reference Colorimeter

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ABSTRACT

The Optical Technology Division at the National Institute of Standards and Technology (NIST) developed a reference instrument for measuring the surface color of non-fluorescent samples at the standard measuring geometries of 0°/45°, ~0°/d, and 8°/d with high accuracy. In addition, this instrument is capable of measuring the full Bi-directional Reflectance Distribution Function (BRDF) of colored samples.

1. INTRODUCTION

The National Institute of Standards and Technology (NIST) has been providing Standard Reference Materials (SRMs) and calibration measurement services for spectral reflectance for many years, although not specifically tailored to the needs of colorimetry. In response to recommendations by industry, the Optical Technology Division at NIST developed a reference goniospectrometer for measuring the surface color of materials under the geometrical and spectral conditions specified by documentary standards for color measurements. The geometrical conditions fall into two categories: bi-directional and directional-hemispherical which are widely used in color measurements. In addition, a five axis goniometer has been implemented to measure the full Bi-directional Reflectance Distribution Function (BRDF). This instrument measures the spectral reflectance factors of non-fluorescent samples, from which the tristimulus values and other color values are calculated for a given illuminant and observer.

2. DESCRIPTION OF NIST REFERENCE COLORIMETER

The illuminator consists of two selectable sources, a Xe arc lamp for wavelengths of 460 nm and shorter and a quartz-tungsten-halogen incandescent lamp for longer wavelengths. The light passes through an order-sorting filter, a double-grating monochromator, a telecentric aperture, an optical chopper, an elliptical focusing mirror, a beam-splitting window, and a polarizer. The radiant flux reflected from the beam-splitting window is measured with a Si photodiode. The illumination at the sample plane is 10 mm by 12 mm with a 5 nm spectral bandwidth and polarization either parallel (0°) or perpendicular (90°) to the plane of illumination. A folding mirror is used to select the measurement geometry. A schematic of the instrument is shown in Figure 1.

The first geometry implemented was the 0°/45° geometry (illumination at 0° and viewing at 45°). A sample wheel with twenty positions contains the specimens and standards; each one is rotated in turn to be illuminated and viewed for a measurement. The receiver consists of a lens, telecentric aperture, silicon photodiode, and current-to-voltage and lock-in amplifiers. A computer is used for automated data acquisition and control. The division now provides a calibration service for the 0°/45° geometry for industrial color standards. Customers either send specimens (typically colored tiles) to NIST for calibration or purchase calibrated standards from NIST.

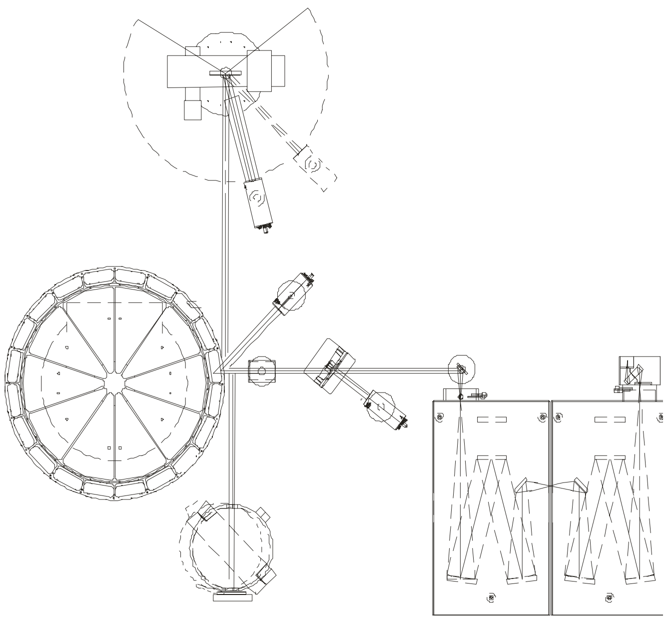

Figure 1. Schematic of NIST Reference Colorimeter

The second measurement geometry is the directional-hemispherical geometry. This geometry is realized by using an integrating sphere with both illumination angles of 0° and 8°. The sphere outer diameter is 30 cm coated with sintered polytetrafluroethylene and the ports are 2.5 cm in diameter.

The third measurement geometry consists of a five axis goniometer that allows bi-directional reflectance measurements over a wide range of illumination and viewing angles for in-plane and out-of-plane geometries. The sample can be rotated in three different axes, allowing illumination from any direction in the hemisphere about the sample with the objective of differentiating between the scattering mechanisms present in gonio-chromatic materials.

3. CHARACTERIZATION AND VALIDATION OF THE 0°/45° MEASURING GEOMETRY

The surface color of a specimen depends upon several factors – the spectral power distribution of the illuminant, the spectral sensitivity of the observer, the geometrical conditions of illumination and observation, and the optical properties of the specimen. Only the last factor depends upon the specimen, and is quantified by the spectral reflectance factor under the given geometrical conditions. Once the spectral reflectance factor is known, the tristimulus values are calculated for a given illuminant and observer, and from these values other quantities are derived, such as chromaticity coordinates or color space values [1].

The measurement of the 0°/45° spectral reflectance factor of a specimen by the NIST reference colorimeter is performed by comparing signals from the customer's specimen and NIST transfer standard, under the same measurement conditions, at each wavelength and polarization of the incident radiant flux. This process is described by the measurement equation

$$R(\lambda_i,\sigma) = \frac{S_{\mathrm{x}}(\lambda_i,\sigma)}{S_{\mathrm{s}}(\lambda_i,\sigma)} \cdot R_{\mathrm{s}}(\lambda_i,\sigma),$$

where λ_i and λ are the wavelength setting and polarization, respectively, of the instrument illuminator, S_{x} and S_{s} are the measured signals from the specimen and NIST transfer standard, respectively, and R and R_{s} are the reflectance factors for the specimen and NIST transfer standard, respectively. The signals are normalized by the signal from a monitor photodiode to account for drift in the radiant flux from the illuminator. Measurements are performed at polarizations of 0° and 90° from the illumination plane, so the reflectance factor of the specimen for unpolarized incident radiant flux is given by the average of these two measurements.

Instrument Characterization	Value
Source System	
Wavelength accuracy	0.05 nm
Stray light	1 x 10^{-6}
Sample Wheel	
Depth position	0.1 %
Illumination angle ± incident angles	0.0 (0.1°) ± 0.9°
Viewing angle ± reflected angles	45.0 (0.1°) ± 1.4°
Detector System	
Linearity	0.2 %
Noise	380 nm to 460 nm: 0.04 % 470 nm to 780 nm: 0.02 %
Reflectance Factor of the Transfer Standard	
Systematic Effects	0.2 %
Random Effects	0.02 %

Table 1: Instrument characterization and the resulting values

The sources of uncertainty for the 0°/45° reference colorimeter were identified from the characterization of the instrument and are listed in Table 1. The primary sources of uncertainty are noise, signal offset such as mis-alignment of the sample and non-linearity of the detector, stray-light, wavelength accuracy, and calibration of the NIST transfer standard. The procedure for determining these uncertainties follows the approach given in [2] and the *ISO Guide to the Expression of Uncertainty in Measurement* [3]. These two references describe methods for estimating uncertainties using a systematic, analytical approach which requires consideration of the measurement equation and the characterization of the measuring instrument.

The uncertainties in L^*, a^*, and b^* for a set of color tiles available from NIST as calibrated standards were calculated for the sources of uncertainties listed in table 1 for CIE Standard Illuminant D65 and the CIE 1964 Standard Observer. The results are given in Table 2 for a representative set of color tiles. The expanded uncertainty U is the root-sum-square of the standard uncertainties from all the sources, multiplied by a coverage factor $k = 2$. While the color difference ΔE is strictly applicable only to comparisons between two different specimens, it is used here as a combined uncertainty from uncertainties is *L**, *a**, and *b**, given by

$$\Delta E = \sqrt{u^2(L^*) + u^2(a^*) + u^2(b^*)}\ .$$

For the neutral color tiles (black, deep gray, mid gray, diff gray, pale gray, and white), there is negligible uncertainty due to stray-light and wavelength since the spectral shapes of the reflectance factors of these specimens are similar to that of the standard. The uncertainties due to signal offset affect only the uncertainty in *L** and are generally directly proportional to *L**, whereas uncertainties due to repeatability affect the uncertainties in *L**, *a**, and *b** and are generally inversely proportional to *L**.

For the colored color tiles (deep pink, red, orange, yellow, green, diff green, cyan, and deep blue), uncertainties from all the sources contribute to the combined uncertainties in *L**, *a**, and *b**. Uncertainties due to noise affect all the color space values, and are roughly directly proportional to *L**, as are uncertainties due to signal offset. Uncertainties due to signal stray-light depend on the spectral shape of the reflectance factor, and are largest for those colors with rapid changes from low to high reflectance factor (red, orange, and yellow). Finally, uncertainties due to wavelength are essentially equal for all the colored color tiles. Overall, those color tiles whose reflectance factors have a spectral shape similar to that of the standard have the lowest uncertainties in color space values.

A tri-lateral comparison of 0/45 color scales between NIST, the National Research Council of Canada (NRCC), and the National Physics Laboratory (NPL) is being conducted to reduce technical barriers to international trade. This comparison includes the exchange of 14 BCRA Series II color tiles.

Conclusions and Future Work

An uncertainty analysis for the CIELAB color space values *L**, *a**, and *b** was performed for the NIST reference colorimeter operating in the 0°/45° geometry for a set of BCRA Series II color tiles available from NIST as calibrated standards. The Δ*E* for all tiles is less than 0.5. The resulting uncertainties in the reflectance factors depend on the optical properties of the sample, and are lowest for the neutral color tiles – those whose spectral shape is similar to that of the standard. The uncertainties presented are those listed in the calibration report that accompanies a set of calibrated color tiles. The same uncertainty analysis is being applied to other measuring geometries including ~0°/d and 8°/d.

Table 2: Standard, *u*, and expanded (k = 2), *U*, uncertainties of the CIELAB values *L**, *a**, and *b** for each source of uncertainty for CIE Illuminant D65 and the CIE 1964 Standard Observer and the indicated color tiles. The sources of uncertainty are A – noise, B – signal offset, C – signal stray-light, D – wavelength, E – reflectance factor of the standard from random effects, and F – reflectance factor of the standard from systematic effects.

Color Tile	Value		Source of Uncertainty A	B	C	D	E	F	*U*
			Standard Uncertainty *u*						
Black	*L**	5.63	0.026	0.014	0.006	0.000	0.000	0.014	0.07
	*a**	-1.25	0.042	0.001	0.003	0.002	0.001	0.001	0.08
	*b**	0.06	0.056	0.000	0.020	0.000	0.001	0.000	0.12
	Δ*E*		0.074	0.014	0.021	0.002	0.001	0.014	0.16
Deep Gray	*L**	26.92	0.006	0.029	0.005	0.000	0.000	0.029	0.08
	*a**	0.02	0.006	0.000	0.002	0.000	0.001	0.000	0.01
	*b**	1.25	0.027	0.001	0.017	0.000	0.001	0.001	0.06
	Δ*E*		0.028	0.029	0.018	0.001	0.001	0.029	0.10
Mid Gray	*L**	57.61	0.004	0.049	0.000	0.000	0.001	0.049	0.14
	*a**	-0.08	0.011	0.000	0.000	0.000	0.002	0.000	0.02
	*b**	0.57	0.017	0.000	0.001	0.000	0.002	0.000	0.04
	Δ*E*		0.021	0.049	0.001	0.001	0.003	0.049	0.15

Diff Gray	L^*	58.17	0.003	0.049	0.000	0.000	0.001	0.049	0.14
	a^*	-2.30	0.006	0.002	0.000	0.001	0.002	0.002	0.01
	b^*	2.58	0.012	0.002	0.001	0.004	0.002	0.002	0.03
	ΔE		0.014	0.050	0.001	0.004	0.003	0.050	0.14
Pale Gray	L^*	83.42	0.002	0.066	0.000	0.000	0.001	0.066	0.19
	a^*	-0.39	0.008	0.000	0.000	0.000	0.002	0.000	0.02
	b^*	0.42	0.011	0.000	0.001	0.001	0.002	0.000	0.02
	ΔE		0.014	0.066	0.001	0.001	0.003	0.066	0.19
White	L^*	95.97	0.010	0.075	0.000	0.000	0.001	0.075	0.21
	a^*	-0.35	0.007	0.000	0.000	0.000	0.003	0.000	0.01
	b^*	1.17	0.010	0.001	0.001	0.001	0.003	0.001	0.02
	ΔE		0.016	0.075	0.001	0.001	0.004	0.075	0.21
Deep Pink	L^*	40.10	0.009	0.037	0.006	0.010	0.000	0.037	0.11
	a^*	28.21	0.019	0.019	0.008	0.009	0.001	0.019	0.07
	b^*	3.92	0.037	0.003	0.015	0.031	0.001	0.003	0.10
	ΔE		0.043	0.042	0.018	0.034	0.002	0.042	0.17
Red	L^*	37.14	0.010	0.035	0.013	0.022	0.000	0.035	0.11
	a^*	48.98	0.015	0.033	0.020	0.023	0.001	0.033	0.11
	b^*	35.26	0.031	0.024	0.141	0.036	0.001	0.024	0.31
	ΔE		0.036	0.054	0.143	0.048	0.002	0.054	0.35
Orange	L^*	64.29	0.010	0.054	0.006	0.021	0.001	0.054	0.16
	a^*	42.49	0.023	0.028	0.008	0.028	0.001	0.028	0.11
	b^*	58.46	0.090	0.039	0.086	0.034	0.002	0.039	0.28
	ΔE		0.094	0.072	0.087	0.049	0.002	0.072	0.34
Yellow	L^*	81.80	0.007	0.065	0.002	0.011	0.001	0.065	0.19
	a^*	2.06	0.025	0.001	0.003	0.030	0.002	0.001	0.08
	b^*	85.21	0.044	0.057	0.096	0.022	0.002	0.057	0.27
	ΔE		0.051	0.086	0.096	0.039	0.003	0.086	0.34
Green	L^*	53.49	0.012	0.046	0.001	0.006	0.001	0.046	0.13
	a^*	-33.72	0.041	0.023	0.004	0.000	0.002	0.023	0.10
	b^*	17.74	0.038	0.012	0.011	0.039	0.001	0.012	0.12
	ΔE		0.057	0.053	0.012	0.039	0.002	0.053	0.21
Diff Green	L^*	53.56	0.013	0.046	0.001	0.005	0.001	0.046	0.13
	a^*	-33.15	0.032	0.022	0.005	0.003	0.002	0.022	0.09
	b^*	21.63	0.029	0.014	0.014	0.038	0.001	0.014	0.11
	ΔE		0.044	0.053	0.015	0.039	0.002	0.053	0.19
Cyan	L^*	52.69	0.012	0.046	0.002	0.013	0.001	0.046	0.13
	a^*	-19.43	0.047	0.013	0.001	0.035	0.002	0.013	0.12
	b^*	-29.60	0.033	0.020	0.004	0.031	0.002	0.020	0.11
	ΔE		0.059	0.052	0.005	0.049	0.003	0.052	0.21
Deep Blue	L^*	11.02	0.009	0.018	0.014	0.005	0.000	0.018	0.06
	a^*	20.14	0.103	0.013	0.025	0.018	0.001	0.013	0.22
	b^*	-32.76	0.101	0.022	0.010	0.026	0.001	0.022	0.22
	ΔE		0.144	0.031	0.030	0.032	0.001	0.031	0.31

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