NIST Reference Goniophotometer for Specular Gloss Measurements

Maria E. Nadal and E. Ambler Thompson—National Institute of Standards and Technology*

The measurement of specular gloss consists of comparing the luminous reflectance from a test specimen to that from a gloss standard, under the same geometric conditions. The reference goniophotometer described here was designed and characterized to comply with the geometric and spectral conditions specified in the international documentary standards for specular gloss measurements at the standard geometries of 20, 60, and 85°. In addition, this instrument measures the bi-directional luminous reflectance and transmittance for incident angles from 0 to 85°. The goniophotometer and the measurement procedures used to determine the specular gloss of nonmetallic samples are described in this paper, as well as the characterization of the instrument and uncertainty analysis. The minimum relative expanded uncertainty (k=2) for the reference goniophotometer is 0.3%.

INTRODUCTION

The current global economy has increased international competition and the need to improve the quality of many manufactured products. Appearance measurements are used to determine the quality and acceptability of a variety of products from textiles to machine finishes. Since the manufacture and marketing of these products is international in scope, the methods, instruments, and standards for the measurement of appearance must be precise, reproducible, and internationally standardized as well.

The appearance of an object is the result of a complex interaction of the light incident on the object, the optical characteristics of the object, and human perception. The scientific basis for the measurement of appearance attributes has been under investigation for the better part of a century and many appearance attributes measurements have been standardized by the Commission Internationale de l'Eclairage (CIE).[1] The visual response of human observers to wavelengths of light for the spectral region of 360 to 830 nm is tabulated as the CIE standard observer. The CIE has defined a series of standard spectral distributions that are known as the CIE Standard Illuminants.

Appearance attributes of an object are roughly divided into chromatic and geometric. The chromatic attributes are those that vary the spectral distribution of the reflected light (color). The geometric attributes are those that vary the spatial or angular distribution of the reflected light (gloss and haze).

This paper describes the reference goniophotometer at the National Institute of Standards and Technology (NIST). This instrument complies with the geometrical and spectral conditions specified by the American Society for Testing and Materials (ASTM) D 523[2] and the International Organization for Standardization (ISO) 2813[3] documentary standards for the measurement of specular gloss of nonmetallic surfaces at fixed specular geometries of 20, 60, and 85°. Gloss measurements for other industrial applications using different geometries can also be accommodated. This goniophotometer is also capable of characterizing the distribution of unabsorbed incident radiation by reflection or transmission from a material at incident angles from 0 to 85°, in compliance with ASTM E 167.[4] *Figure* 1 shows a plot of the luminous reflectance as a function of the observation angle for a set of black glasses with different values of gloss.

Interest in gloss measurements at the National Bureau of Standards (NBS, as it was previously called) dates back to the 1930s.[5-7] The goniophotometer described in this paper was originally developed at NBS[8] in the 1970s by scientists active in the development of the ASTM standard test method and has recently been updated, automated, and characterized. The instrument was revived to meet

*Optical Technology Div., Gaithersburg, MD 20899-8441.

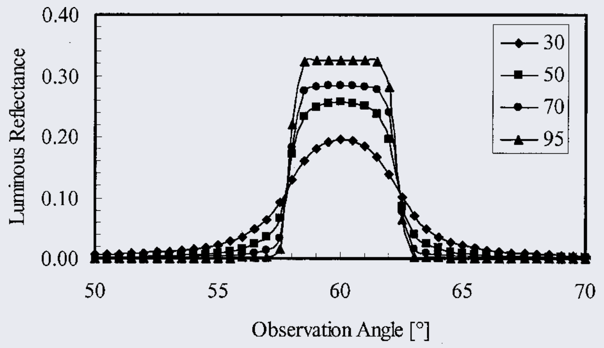

Figure 1—Luminous reflectance as a function of observation angle for a set of black glass with different levels of gloss as indicated in the legend.

industrial needs, such as the paint and automotive industries, for accurate gloss measurements and direct traceability to national standards.

GLOSS DEFINITION AND MEASUREMENT EQUATIONS

This section details the basic definitions and the relevant measurement equations to determine specular gloss. The approach utilized in this paper is based upon the concepts presented in references 8-10.

Gloss is the perception by an observer of the shiny appearance of a surface. This perception changes whenever there is a change in the relative position or spectral distribution of the source, the sample, and the observer. Different standard geometries are used to determine the specular gloss of materials. *Table* 1 lists examples of these geometries and their applications. These geometries were selected based on their ability to produce optimum discrimination between samples and to correlate with visual rankings.

Table 1— Standard Geometries for Specular Gloss Measurements and Their Applications

Specular Angle	Applications
20°	High gloss of plastic film, appliance and automotive finishes
30°	High gloss of image-reflecting surfaces
45°	Porcelain enamels and plastics
60°	All ranges of gloss for paint and plastics
75°	Coated waxes and paper
85°	Low gloss of flat matte paints and camouflage coatings

Table 2— Specular Reflectance $\rho_0(\theta, \lambda_D)$ of the Theoretical Gloss Standard for Each Incident Angle of the Standard Geometries at Wavelength λ_D = 589.3 nm

Incident Angle	$\rho_0(\theta, \lambda_D)$
20°	0.049078
60°	0.100056
85°	0.619148

The measurement of specular gloss compares the specular luminous reflectance from a test specimen to that from a standard surface under the same experimental conditions. The incident beam is a collimated white light source that simulates CIE Standard Illuminant C, and the amount of radiation in the reflected beam is measured with a photopic receptor. The theoretical standard for specular gloss measurements is a highly polished plane black glass with a refractive index for the sodium D line $n_D = 1.567$. To set the specular gloss scale, the specular gloss of this theoretical standard has an assigned value of 100 for each of the three standard specular geometries of 20, 60, and 85°. For primary standards with a refractive index different from $n_D = 1.567$, the specular gloss is computed from the refractive index and the Fresnel equations. Recommendations for specular gloss standards and a new NIST primary gloss standard are described in reference 11.

Measuring the specular gloss of a test sample involves the ratio of the luminous reflectances of the test sample and primary standard. The specular gloss of a test sample at a nominal angle θ_0 is given by

$$G_t(\theta_0) = G_s(\theta_0) \cdot \frac{\rho_{v,t}(\theta_0)}{\rho_{v,s}(\theta_0)} \quad (1)$$

where $G_s(\theta_0)$ is the specular gloss of the primary standard and $\rho_{v,t}(\theta_0)$ and $\rho_{v,s}(\theta_0)$ are the specular luminous reflectances of the test sample and primary standard, respectively. Furthermore, the specular gloss of the primary standard is given by

$$G_s(\theta_0) = G_0(\theta_0) \cdot \frac{\rho_s(\theta_0, \lambda_D)}{\rho_0(\theta_0, \lambda_D)} \quad (2)$$

where $G_0(\theta_0)$ is the specular gloss of the theoretical standard and $\rho_s(\theta_0, \lambda_D)$ and $\rho_0(\theta_0, \lambda_D)$ are the specular reflectances of the primary and theoretical standards, respectively, at a wavelength λ_D = 589.3 nm. Combining equations (1) and (2), the specular gloss of the sample under test is given by

$$G_t(\theta_0) = G_0(\theta_0) \cdot \frac{\rho_s(\theta_0, \lambda_D)}{\rho_0(\theta_0, \lambda_D)} \cdot \frac{\rho_{v,t}(\theta_0)}{\rho_{v,s}(\theta_0)} \quad (3)$$

For each of the three standard geometries (20, 60, and 85°), the specular gloss of the theoretical standard is defined as $G_0(\theta_0) = 100$. The specular reflectance ρ from the surface of a nonmetallic sample depends on the incident angle θ defined relative to the normal of the sample, the wavelength λ, and polarization σ (p or s) of the incident radiation. The specular reflectance as a function of these variables is given by the Fresnel equations,

$$\rho(\theta, \lambda, p) = \left[\frac{n^2(\lambda) \cdot \cos\theta - \sqrt{n^2(\lambda) - \sin^2\theta}}{n^2(\lambda) \cdot \cos\theta + \sqrt{n^2(\lambda) - \sin^2\theta}} \right]^2 \quad (4)$$

$$\rho(\theta, \lambda, s) = \left[\frac{\cos\theta - \sqrt{n^2(\lambda) - \sin^2\theta}}{\cos\theta + \sqrt{n^2(\lambda) - \sin^2\theta}} \right]^2 \quad (5)$$

The specular reflectance for unpolarized light is calculated from the average of equations (4) and (5). The specular reflectances for unpolarized light for the theoretical standard $\rho_0(\theta_0, \lambda_D)$ with $n_D = 1.567$ are calculated from equations

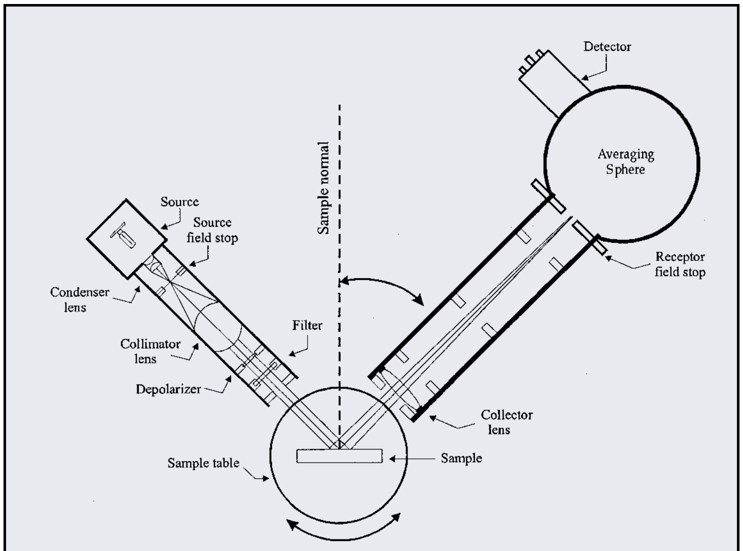

Figure 2—A schematic diagram of the NIST reference goniophotometer.

(4) and (5) and are listed in *Table* 2. For the case of the NIST new primary gloss standard,[11] the specular reflectances are calculated from the measured $n_D = 1.5677 \pm 0.0004$ and equations (4) and (5).

The components of uncertainty associated with gloss measurements are divided into those arising from experimentally measured quantities and those from deviations from standard recommendations. The experimentally measured quantities include the source stability, responsivity of the detector, photodiode linearity, digital voltmeter, amplifier gain ratio, and signal noise. Deviations of the reference instrument from the standard recommendations include deviations from the specified spectral flux distribution of the source, spectral responsivity of the receptor, unpolarized and perfectly collimated incident beam, and nominal incident angle. The resulting uncertainty from deviations from the standard recommendations depends on the nature of the sample under test and the primary standard. Details of the derivation of the measurement equations to determine the components of uncertainty associated with gloss measurements are given in *Appendix* A.

INSTRUMENT DESIGN

The reference goniophotometer is a monoplane gonioinstrument with a fixed source arm, a rotating sample table and receptor arm. The sample table and the receptor arm can be rotated independently of each other in the plane of incidence. A schematic diagram of the goniophotometer in reflectance mode is shown in *Figure* 2 and a detailed description of the instrument is given.

The source system consists of a lamp unit, a set of condenser lenses, a precision source aperture, a collimating lens, and a color filter. The light source is a quartz-tungsten-halogen lamp rated at 100 W. A constant dc current is run through the lamp from a computer controlled power supply. An image of the lamp filament is formed on the source aperture with an achromatic condenser lens system. This source aperture is the field stop for this optical system. The dimensions of the source aperture are within the tolerances of the documentary standard specifications as shown in *Table* 3. A second lens (focal length 192 mm) collimates the beam into an approximate 3 cm diameter beam at the sample holder. A color filter is used so that the spectral flux distribution of the source-filter combination closely resembles that of CIE Standard Illuminant C. A glass-laminated polarizer is used to provide linearly polarized light or a scrambler is used to provide unpolarized light as the incident beam.

The goniometer positions the sample and receptor for bi-directional reflectance and transmittance measurements. This goniometer consists of two rotation stages, which are computer controlled. The sample table is 480 mm in diameter and holds rectangular samples with dimensions up to 100 by 200 mm and thickness up to 25 mm. In addition, a sampler holder with vacuum suction is used for non-rigid samples such as paper. The optical components for the receptor arm are enclosed in a light-tight baffle tube with an iris diaphragm at the entrance. The collector lens (focal length 508 mm) is behind this iris diaphragm and focuses the reflected beam at the receptor aperture. *Table* 3 lists the recommended dimensions of the receptor aperture with specified tolerances and the measured dimensions for the NIST apertures. This aperture is located at the entrance of the sphere to restrict the field of view of the receptor. The receptor package consists of a 30.5 cm diameter sphere packed with pressed polytetrafluoroethylene (PTFE) and a photopic receptor. The photopic receptor is a temperature controlled silicon photodiode and a filter with a computer controlled variable gain current to voltage amplifier. The photodiode-filter combination approximates $V\lambda$. The amplified output from the receptor is measured by a 6 1/2-digit voltmeter and sent to a computer.

Measurements of the sample under test are bracketed with primary specular gloss standard measurements in order to correct for any instrumental drift. The specular gloss of the test sample is then calculated from the ratio of the measured luminous flux reflected from the sample to the average of the measured luminous flux reflected from the primary gloss standard. If a polarizer is used, measurements are performed with parallel and perpendicular polarization with respect to the incident plane, and the aver-

Table 3—ASTM Specifications and the NIST Measured Values for Source and Receptor Apertures, with Tolerances and Uncertainties, Respectively

	In Plane (°)		Perpendicular to the Plane (°)	
Apertures	ASTM Spec.	NIST Apertures	ASTM Spec.	NIST Apertures
Source	0.75 ± 0.25	0.75 ± 0.01	3.0(max.) ± 0.5	3.01 ± 0.01
20° Receptor........	1.8 ± 0.05	1.82 ± 0.01	3.6 ± 0.1	3.64 ± 0.02
60° Receptor........	4.4 ± 0.1	4.44 ± 0.02	11.7 ± 0.2	11.72 ± 0.01
85° Receptor........	4.0 ± 0.3	4.03 ± 0.01	6.0 ± 0.3	6.02 ± 0.01

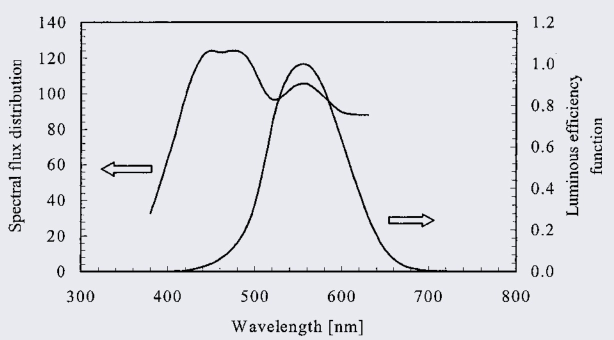

Figure 3—Spectral flux distribution of the CIE Standard Illuminant C and CIE 1931 2° luminous efficiency function.

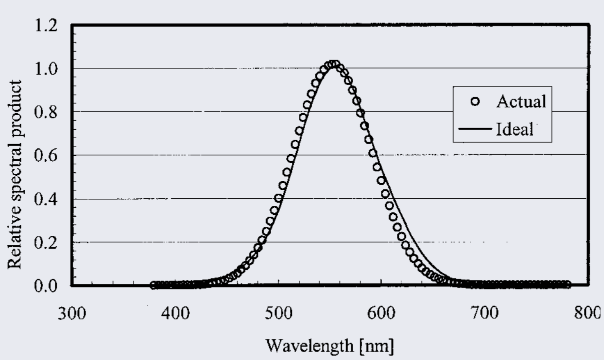

Figure 4—Actual and ideal spectral products of the source and receptor.

age of these two measurements yields the reflectance for unpolarized radiation.

CHARACTERIZATION OF INSTRUMENT

This instrument has been carefully characterized and calibrated to ensure proper operation and to verify agreement with the documentary standard specifications for specular gloss measurements—ASTM D 523 and ISO 2813. These documentary standards specify the incident beam to be a collimated unpolarized beam, the specular angles, the source and receptor apertures, and the spectral flux distribution of the source and spectral response of the receptor. Details of the characterization of the instrument follow.

The lamp is burned in at 100 W for 24 hr and then at the operational current of 6.3 A for an additional 48 hr prior to performing measurements. The stability of the source was investigated by measuring the flux incident on a Si photodiode at the sample location for a period of 30 min. A typical relative standard deviation over 10 min is 0.01%.

The degree of polarization of the source unit was measured by rotating a polarizer and measuring the maximum and minimum transmitted signals. The difference of the signals was divided by the sum to obtain the degree of polarization of the source. This ratio is approximately nine percent. Because the light source is not completely unpolarized, a glass-laminated polarizer or scrambler is used in the beam path just before the sample. The averaging sphere on the receptor arm in front of the photopic receptor randomizes any additional polarization imparted by the sample. The leakage of the glass-laminated polarizer for radiation that is polarized perpendicular to the intended direction of polarization on the source unit is 1.4%. The degree of polarization of the source-scrambler combination is 0.02%, providing a good beam of unpolarized incident radiation. The divergence of the source was determined experimentally by measuring the source size at specific distances. In the plane of measurement, the half-angle divergence of the source is 0.3°.

The recommended spectral condition for specular gloss measurements is for the source to simulate the spectral distribution of CIE Standard Illuminant C and for the receptor response to simulate the CIE 1931 2° luminous efficiency function. The spectral distributions of these standards are shown in *Figure* 3.

A color filter was designed so that the spectral flux distribution of the source-filter combination will closely resemble that of CIE Standard Illuminant C. The correlated color temperature (CCT) and the spectral flux distribution of the source for the spectral range of 380 to 1070 nm were measured using a calibrated scanning spectroradiometer.[12] A freshly pressed PTFE sample[13] was placed in the sample holder at an incident angle of 45° and an observation angle of ~0°. The spectral reflectance of PTFE is nonselective in the visible region. Therefore, the PTFE sample has no significant effect on the measured CCT of the source. The lamp current is set at 6.3 A to achieve a CCT of 2856 K ± 10 K with a coverage factor of $k = 2$. A color-temperature conversion filter was designed to simulate the spectral flux distribution of CIE Standard Illuminant C (CCT = 6774 K), achieving a CCT of 6740 K ± 30 K with a coverage factor of $k = 2$.

The absolute spectral responsivity of the filter and receptor package was measured in the NIST Detector Comparator Facility,[14] and approximates that of the CIE 1931 2° standard observer. The measured spectral distribution was normalized to one at 560 nm to compare with the theoretical distribution. The responsivity spatial uniformity of the receptor was not determined since an integrating sphere is used in front of the receptor. *Figure* 4 shows a comparison of the spectral products of the source and receptor and of the CIE Standard Illuminant C and the 1931 2° luminous efficiency function.

The angular scales of the sample table and receptor were checked for accuracy and repeatability from 0 to ±85°. The incident angles on the sample table are calibrated using a set of isosceles prisms made by the NIST optical shop. These prisms have nominal base angles of 20, 60, and 85° with maximum deviations of 0.05°. These angles correspond to the standard geometries for evaluation of the specular gloss of nonmetallic paint samples. The prisms were calibrated by the Manufacturing Engineering Laboratory at NIST using a precision electronic autocollimator with an expanded uncertainty ($k = 2$) of 0.005°.[15] For the calibration of the incident angles, one of the calibrated prisms was mounted in the sample holder. The sample table was then

Table 4—Average Gain Ratio and Relative Standard Deviation for Successive Amplifier Gain Ratios

Gain Ratio	Average Value	Relative Standard Deviation (%)
G_6/G_5	9.999	0.002
G_7/G_6	9.998	0.002
G_8/G_7	9.997	0.002
G_9/G_8	10.017	0.003
G_{10}/G_9	9.952	0.003

rotated so that the back reflection was retro-reflected. This procedure was repeated for the three prisms, the resulting maximum uncertainty for the angular scale of the sample table is 0.05°. The repeatability of the angular scale for the sample table is 0.005°. Then, to calibrate the receptor angular scale, a front surface mirror replaced the prism and the reflection was centered in the receptor aperture by rotating the receptor arm. The maximum uncertainty for the receptor arm angular scale is 0.05° and the repeatability is 0.001°.

The dimensions of the source and receptor apertures are predetermined by the specular geometry, focal length of the collimator lens in the system, test material, and the correlation with visual ranking. *Table* 3 lists the standard recommended aperture sizes and acceptable tolerances and measured values for the NIST apertures. The linear dimensions of the apertures were measured, and the angular dimensions were calculated. All of the apertures are within the ASTM tolerances.

The photopic receptor consists of a temperature controlled silicon photodiode with a photopic filter and a computer controlled variable gain current to voltage amplifier. The gain setting of the amplifier is the power of 10 by which the current is multiplied to convert it to voltage. For low gloss samples, the measured signal is much lower than the signal from the high specular gloss primary standard. In this case, several amplifier gain settings are required to cover the dynamic range. From equation (A2), the ratio of the gain is the required quantity. The gain settings of the amplifier were calibrated using a reference constant current source as the input of the amplifier, and a voltmeter was used to measure the output signal. At each gain setting, the current was set to obtain a range of voltages from 10 to 0.1 V in 20 equally spaced steps and the output signal was measured at each current. This protocol yielded current settings that were common to successive gain settings. The average value of the gain ratio and relative standard deviation of these overlapping settings for successive gains are listed in *Table* 4. The gain ratios are not exactly equal to 10, and for better results, it is best to measure signals between the range of 0.5 to 12 V.

The linearity of the photodiode-amplifier combination was measured using the NIST automated beam conjoiner.[16] This facility uses the beam addition method with a set of filters in the path of the two branches of the beam to vary the radiant flux at the receptor by three decades. The linearity of the photodiode-amplifier combination was checked at gain settings from 5 to 9. The maximum radiant flux at the receptor is controlled by a set of neutral-density filters in front of the receptor. *Figure* 5 shows a plot of the relative responsivity (ratio of the measured signal to the actual flux) as a function of current for the gain settings listed in the legend. The measured relative responsivity of the photodiode-amplifier combination is linear within 0.2% for gain settings of 5 to 8. Larger deviations are observed at gain 9 due to the small current at this setting.

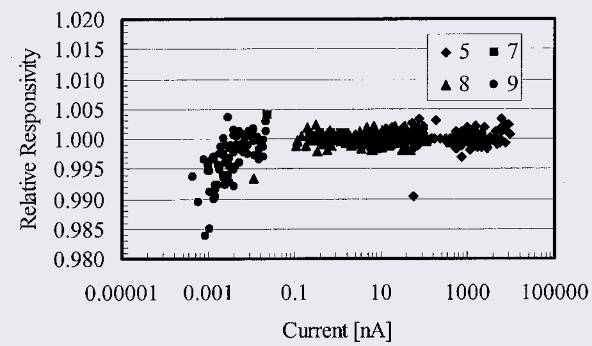

Figure 5—Relative responsivity (ratio of the measured signal to the actual flux) of the photodiode-amplifier combination as a function of current for the listed gain settings.

UNCERTAINTY ANALYSIS

This section describes the components of uncertainty, their evaluation, and the resulting uncertainty for specular gloss measurements. The uncertainty analysis described follows the guidelines given in reference 17. The NIST reference goniophotometer was designed so that the various sources of uncertainty were minimized and the residual uncertainties were characterized to produce specular gloss with a minimum relative expanded uncertainty ($k = 2$) of 0.3%.

The specular gloss of a test sample is not measured directly. In fact, specular gloss is determined from quantities such as incident and reflected fluxes through the measurement equation. In general, the value of a measurand, y, is obtained from n other quantities x_i through a functional relation, f, given by

$$y = f(x_1, x_2, \cdots, x_i, \cdots, x_n) \quad (6)$$

The standard uncertainty of an input quantity is the estimated standard deviation associated with this quantity and is denoted by $u(x_i)$. The standard uncertainties are classified by the effect of their source and the method of evaluation. The effect is either random or systematic. The method of evaluation is either Type A, which is based on statistical analysis, or Type B, which is based on other means. The relative standard uncertainty is given by $u(x_i)/x_i$. The relative combined standard uncertainty $u_c(y)$ is given by the root-sum-square of the standard uncertainties associated with each quantity x_i, assuming that these uncertainties are uncorrelated for multiplicative functional relationships. The mathematical expression for the relative combined standard uncertainty is

$$u_c^2(y)/y^2 = \sum_{i=1}^{n}\left(\frac{1}{y}\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) \quad (7)$$

where $(1/y)(\partial f/\partial x_i)$ is the relative sensitivity coefficient. The expanded uncertainty U is given by $k \cdot u_c(y)$, where k is

Table 5—Correction Factors for Deviations from the Standard Recommendations of an Unpolarized Source, a Perfectly Collimated Incident Beam, Nominal Incident Angle of 20, 60, and 85°, and Spectral Conditions

Deviation	Correction Factors 20°	60°	85°
Source-polarizer, C_p	0.999890	1.000137	1.000222
Source-depolarizer, C_p	0.999999	1.000001	0.999995
Divergence, C_d	0.999999	0.999806	0.999999
Nominal angle, C_a	0.999996	0.999875	0.999940
Spectral condition, C_s	1.000012	1.000006	0.999997

the coverage factor and is chosen on the basis of the desired level of confidence to be associated with the interval defined by U. For the purpose of this paper, $k = 2$ will be used, which defines an interval with a level of confidence of 95%.

The components of uncertainty associated with gloss measurements are divided into those arising from experimentally measured quantities and those from deviations from standard recommendations. The appropriate measurement equation for the first case is equation (A2) and for the latter case equations (A8) to (A12) are applicable. The resulting uncertainty from deviations from the standard recommendations depends on the nature of the sample under test and the primary standard. This uncertainty analysis was applied to representative measurements of a highly polished black glass as the test sample and to a highly polished wedge of BaK50 as the primary standard.

The component of uncertainty arising from the specular reflectance of the primary gloss standard is uncertainty in the refractive index measurements. The uncertainties from the refractive index measurements are a systematic effect with a Type B evaluation. The relative uncertainty resulting from the refractive index measurements is 0.1, 0.06, and 0.005% for the 20, 60, and 85° geometries, respectively.

The components of uncertainty arising from the source are uncertainties from the stability, polarization, and divergence of the source. The source stability results in an uncertainty from a random effect with a Type A evaluation. The relative standard uncertainty due to instability of the source is 0.001% for a measurement time of 10 min. The uncertainty arising from the polarization of the source is a systematic effect with a Type B evaluation and depends on the scattering properties of the material. The correction factor for deviations from an unpolarized incident beam was calculated from equation (A9) using the degrees of polarization determined in the previous section. The correction factors for the three standard geometries are listed in *Table* 5. The uncertainty arising from divergence of the source is a systematic effect with a Type B evaluation and depends on the scattering properties of the material. The correction factor for deviations from a perfectly collimated incident beam was calculated from equation (A10) using the divergence determined in the previous section. The correction factors for the three standard geometries are listed in *Table* 5.

The uncertainty arising from the goniometer are the uncertainties of the angular scales. This uncertainty is a systematic effect with a Type B evaluation and depends on the scattering properties of the sample. The angular setting uncertainty of 0.05° is smaller than the 0.1° recommended accuracy by the ASTM D 523. The correction factors from deviations of the nominal incident angle from equation (A11) for the three standard geometries are listed in *Table* 5.

The components of uncertainty arising from the detection system are uncertainties from the digital voltmeter (DVM), signal noise, amplifier gain ratio, and photodiode linearity. The uncertainty from the DVM is a systematic effect with a Type B evaluation, assuming a normal probability distribution. Using the manufacturer's specifications, the relative uncertainty resulting from the DVM is 0.002%. Signal noise of the instrument results in an uncertainty from a random effect with a Type A evaluation. A typical relative standard deviation for a gloss measurement is 0.01%. The uncertainties arising from the photodiode linearity and the amplifier gain ratio are systematic effects with a Type A evaluation. The maximum relative standard deviation from linearity of the photodiode, for signals in the range of 0.1 to 12 V, is 0.09%. The relative standard deviations for successive gain settings are listed in *Table* 4. The maximum relative standard deviation is 0.002%.

The repeatability of the sample positioning results in an uncertainty from a random effect with a Type B evaluation. Assuming a rectangular probability distribution with a maximum deviation of 0.2 gloss units, the relative standard uncertainty is 0.1%.

Deviations from the spectral condition are important for low-gloss materials with strong colors. The spectral conditions of the source and re-

Table 6a—Components of Uncertainty that Depend on the Scattering Properties of the Materials and the Resulting Relative Standard Uncertainties[a]

Component of Uncertainly	Effect	Type	Relative Standard Uncertainty (%) 20°	60°	85°
Source-polarizer	S	B	0.01	0.01	0.02
Source-depolarizer	S	B	0.0001	0.0001	0.0005
Source Divergence	S	B	0.0001	0.02	0.0001
Nominal angle	S	B	0.0004	0.01	0.006
Spectral condition	S	B	0.001	0.0006	0.0003

(a) The values are based on a BaK50 primary gloss standard and a hghly polished black glass test sample.

Table 6b—Components of Uncertainty that are Independent of the Scattering Properties of the Materials and the Resulting Relative Standard Uncertainties

Component of Uncertainty	Effect	Type	Relative standard uncertainty (%) 20°	60°	85°
Primary gloss standard	S	B	0.1	0.06	0.005
Source stability	R	A		0.01	
DVM	S	B		0.002	
Signal noise	R	A		0.01	
Photodiode linearity	S	A		0.09	
Amplifier gain ratio	S	A		0.002	
Repeatability	R	B		0.1	

Table 7—Relative Expanded Uncertainties of Specular Gloss Measured by the NIST Reference Goniophotometer (k = 2) for the 20, 60, and 85° Geometries

Geometry (°)	Relative Expanded Uncertainty (%)
20	0.34
60	0.30
85	0.27

ceptor are in close agreement with the recommended CIE Standard Illuminant C and CIE 1931 2° luminous efficiency function. The difference between the instrument and the standard recommendations results in a systematic effect with a Type B evaluation. The correction factors for deviations from the standard recommendations for the three standard geometries, from equation (A8), are listed in *Table* 5.

Since all of the correction factors listed in *Table* 5 are nearly unity, no correction factor is applied and the variations from unity are considered to be uncertainties. The relative standard uncertainty from each component of uncertainty is listed in *Tables* 6a and 6b for sample-dependent and –independent components, respectively. The relative expanded uncertainties given in *Table* 7 are calculated from the root-sum-square of the uncertainties listed in *Tables* 6a and 6b. The ISO 2813 standard specifies that gloss should be reported to the nearest full gloss unit. Therefore, the calibration of the reference instrument and primary standard should have an uncertainty of less than one gloss unit. The NIST reference goniophotometer has an expanded (k = 2) relative uncertainty of 0.3% for calibrating a highly polished black glass. If the specular gloss of successive measurements on the same sample does not agree to within 0.3%, the instrument is assumed to have failed during the measurements and the sample is measured again.

CONCLUSIONS

The appearance attributes of surfaces indicate the acceptability and quality of a large number of manufactured products. Specular gloss is the second most utilized attribute, after color, to evaluate products such as automotive coatings, textiles, and papers. The reference goniophotometer described in this paper complies with the standard recommendations for specular gloss at 20, 60, and 85° geometries for nonmetallic paint samples from low to high gloss levels, as described in the ISO 2813 and ASTM D 523 documentary standards. In addition, this reference instrument is capable of performing bi-directional reflectance and transmission measurements at angles from 0 to 85° for both incident and viewing angles in compliance with the ASTM E 167 documentary standard. This instrument has been carefully characterized and calibrated to ensure proper operation and to verify agreement with the standard recommendations. The relative expanded uncertainty (k = 2) of the NIST goniophotometer for specular gloss is 0.3% at all three standard geometries. The accuracy of specular gloss measurements depends not only on the properties of the instrument but also to a considerable extent on those of the primary gloss standard. A new primary gloss standard was developed at NIST and details on this standard characterization are the subject of another paper.[11] The new gloss standard and the NIST reference goniophotometer provide an accurate calibration facility for specular gloss.

ACKNOWLEDGMENTS

The authors wish to express special thanks to Edward Early for many useful discussions and the collaboration with the National Institute of Standards and Technology researchers who are working on the Measurement Science for Optical Reflectance and Scattering Project.

References

(1) Commission International de l'Eclairage, *International Lighting Vocabulary, Colorimetry, 2nd ed.*, Publ. No. 15.2, 1986.

(2) "Standard Test Method for Specular Gloss, ASTM D 523," American Society for Testing and Materials, West Conshohocken, PA (1995).

(3) International Standard ISO 2813, "Paint and Varnishes-Measurements of Specular Gloss of Nonmetallic Paint Films at 20, 60, and 85°," International Organization for Standardization (1978).

(4) "Standard Practice for Goniophotometry of Objects and Materials, ASTM E 167," American Society for Testing and Materials, West Conshohocken, PA (1995).

(5) Hunter, R.S., "Gloss Investigations Using Reflected Images of a Target Patters," *J. Res.*, 16, 359 (1936).

(6) Hunter, R.S., "Methods of Determining Gloss," NBS Research Paper RP 958, *J. Res.*, 18, No. 77, 281 (1937).

(7) Nimeroff, I. "Analysis of Goniophotometric Reflective Curves," *J. Res*, 48, No. 5, 441 (1952).

(8) Hsia, J.J., *The NBS 20-, 60-, and 85- Degree Specular Gloss Scales*, NIST Technical Note 594-10, 1975.

(9) Nicodemus, F.E., Richmond, J.C., Hsia, J.J., Ginsburg, I.W., and Limperis, T., *Geometrical Considerations and Nomenclature for Reflectance*, U.S. NBS Monograph 160, 1977.

(10) Budde, W., "The Calibration of Gloss Reference Standards," *Metrologia*, 16, 89-93 (1980).

(11) Nadal, M.E. and Thompson, E.A., "New Primary Standard for Specular Gloss Measurements," Journal of Coatings Technology, 72, No. 911, 61 (2000).

(12) Ohno, Y., *Photometric Calibrations*, NIST SP 250-37, 1997.

(13) Barnes, P.Y. and Hsia, J.J., *45°/0° Reflectance Factor of Pressed Polytetrafluoroethylene (PTFE) Powder*, NIST Technical Note 1413, 1995.

(14) Larson, T.C., Bruce, S.S., and Parr, A.C., *Spectroradiometric Detector Measurements*, NIST SP 250-41, 1998.

(15) Doiron, T. and Stoup, J., "Uncertainty and Dimensional Calibrations," *J. Res. Natl. Inst. Stand. Technol.*, 102, 647 (1997).

(16) Saunders, R.D. and Shumaker, J.B., "Automated Radiometric Linearity Tester," *Appl. Opt.*, 23, 3504 (1984).

(17) Taylor, B.N. and Kuyatt, C.E., *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurements Results*, NIST Technical Note 1297, 1994.

APPENDIX A: DERIVATION OF MEASUREMENT EQUATION

The experimentally measured quantity is the ratio of the luminous fluxes reflected from the test sample and primary standard, $\Phi_{v,t,r}$ and $\Phi_{v,s,r}$ respectively,

$$\frac{\rho_{v,t}(\theta_0)}{\rho_{v,s}(\theta_0)} = \frac{\Phi_{v,s,i}}{\Phi_{v,t,i}} \cdot \frac{\Phi_{v,t,r}}{\Phi_{v,s,r}} = \frac{\Phi_{v,s,i}}{\Phi_{v,t,i}} \cdot \frac{R_s}{R_t} \cdot \frac{N_t}{N_s} \cdot \frac{A_s}{A_t} \quad \text{(A1)}$$

where R is the responsivity of the receptor, N is the measured signal, A is the amplifier gain factor, and the subscripts s and t denote standard and test sample, respectively. Therefore, combining equations (3) and (A1), the specular gloss of a test sample in terms of the measured quantities reduces to

$$G_t(\theta_0) = 100 \cdot \frac{\rho_s(\theta_0,\lambda_D)}{\rho_0(\theta_0,\lambda_D)} \cdot \frac{\Phi_{v,s,i}}{\Phi_{v,t,i}} \cdot \frac{R_s}{R_t} \cdot \frac{N_t}{N_s} \cdot \frac{A_s}{A_t} \quad \text{(A2)}$$

The stability of the incident flux and responsivity are determined from the characterization of the instrument.

In terms of spectral and geometrical quantities, the luminous reflectance ρ_v of a sample at a nominal angle θ_0 is given by

$$\rho_v(\theta_0) = \frac{\sum_\sigma \int d\theta \int d\lambda \cdot S(\theta,\lambda,\sigma) \cdot \rho(\theta,\lambda,\sigma) \cdot V(\theta,\lambda,\sigma)}{\sum_\sigma \int d\theta \int d\lambda \cdot S(\theta,\lambda,\sigma) \cdot V(\theta,\lambda,\sigma)} \quad \text{(A3)}$$

where S is the incident spectral flux distribution, V is the relative response function, and ρ is the reflectance of the sample. These variables depend on the angle of incidence θ wavelength λ and polarization σ of the incident beam. In practice, the luminous reflectances of the standard and test sample are not measured separately. Rather, the ratio of these reflectances is measured and is given by

$$\frac{\rho_{v,t}(\theta_0)}{\rho_{v,s}(\theta_0)} = \frac{\sum_\sigma \int d\theta \int d\lambda \cdot S(\theta,\lambda,\sigma) \cdot \rho_t(\theta,\lambda,\sigma) \cdot V(\theta,\lambda,\sigma)}{\sum_\sigma \int d\theta \int d\lambda \cdot S(\theta,\lambda,\sigma) \cdot \rho_s(\theta,\lambda,\sigma) \cdot V(\theta,\lambda,\sigma)} \quad \text{(A4)}$$

Then, the specular gloss of a test sample is given by

$$G_t(\theta_0) = 100 \cdot \frac{\rho_s(\theta_0,\lambda_D)}{\rho_0(\theta_0,\lambda_D)} \cdot \frac{\sum_\sigma \int d\theta \int d\lambda \cdot S(\theta,\lambda,\sigma) \cdot \rho_t(\theta,\lambda,\sigma) \cdot V(\theta,\lambda,\sigma)}{\sum_\sigma \int d\theta \int d\lambda \cdot S(\theta,\lambda,\sigma) \cdot \rho_s(\theta,\lambda,\sigma) \cdot V(\theta,\lambda,\sigma)} \quad \text{(A5)}$$

Following the standard recommendations, the incident spectral flux distribution $S(\lambda)$ is specified to be CIE Standard Illuminant C $S_C(\lambda)$ and the relative response function $V(\lambda)$ is specified to be the CIE 1931 2° observer spectral luminous efficiency function $V\lambda$. In addition, the incident beam of light is specified to be collimated and unpolarized at a nominal incident angle θ_0. The specular gloss of the sample under test for the ideal case is given by

$$G_{t,id}(\theta_0) = 100 \cdot \frac{\rho_s(\theta_0,\lambda_D)}{\rho_0(\theta_0,\lambda_D)} \cdot \frac{\int d\lambda \cdot S_C(\lambda) \cdot \rho_t(\theta_0,\lambda) \cdot V_\lambda(\lambda)}{\int d\lambda \cdot S_C(\lambda) \cdot \rho_s(\theta_0,\lambda) \cdot V_\lambda(\lambda)} \quad \text{(A6)}$$

Deviations of the reference instrument from the ideal case include deviations from the specified spectral flux distribution of the source, spectral responsivity of the receptor, unpolarized and perfectly collimated incident beam, and nominal incident angle. The correction factors for the specular gloss of the sample under test as determined with the reference instrument are obtained using equations (A5) and (A6). The correction factors are the ratio of the specular gloss for the ideal case to the specular gloss for the reference instrument

$$C = \frac{G_{t,id}(\theta_0)}{G_t(\theta_0)} \quad \text{(A7)}$$

The correction factor for deviations from the ideal spectral flux distribution is given by

$$C_s = \frac{\int d\lambda \cdot S_C(\lambda) \cdot \rho_t(\theta_0,\lambda) \cdot V_\lambda(\lambda)}{\int d\lambda \cdot S_C(\lambda) \cdot \rho_s(\theta_0,\lambda) \cdot V_\lambda(\lambda)} \cdot \frac{\int d\lambda \cdot S(\lambda) \cdot \rho_s(\theta_0,\lambda) \cdot V(\lambda)}{\int d\lambda \cdot S(\lambda) \cdot \rho_t(\theta_0,\lambda) \cdot V(\lambda)} \quad \text{(A8)}$$

The correction factor for deviations from an unpolarized incident beam is given by

$$C_p = \frac{\int d\lambda \cdot S_C(\lambda) \cdot \rho_t(\theta_0,\lambda) \cdot V_\lambda(\lambda)}{\int d\lambda \cdot S_C(\lambda) \cdot \rho_s(\theta_0,\lambda) \cdot V_\lambda(\lambda)} \cdot \frac{\sum_\sigma \int d\lambda \cdot S_C(\lambda,\sigma) \cdot \rho_s(\theta_0,\lambda,\sigma) \cdot V_\lambda(\lambda)}{\sum_\sigma \int d\lambda \cdot S_C(\lambda,\sigma) \cdot \rho_t(\theta_0,\lambda,\sigma) \cdot V_\lambda(\lambda)} \quad \text{(A9)}$$

The correction factor for deviations from a perfectly collimated incident beam is given by

$$C_d = \frac{\int d\lambda \cdot S_C(\lambda) \cdot \rho_t(\theta_0,\lambda) \cdot V_\lambda(\lambda)}{\int d\lambda \cdot S_C(\lambda) \cdot \rho_s(\theta_0,\lambda) \cdot V_\lambda(\lambda)} \cdot \frac{\int d\theta \int d\lambda \cdot S_C(\theta,\lambda) \cdot \rho_s(\theta,\lambda) \cdot V_\lambda(\lambda)}{\int d\theta \int d\lambda \cdot S_C(\theta,\lambda) \cdot \rho_t(\theta,\lambda) \cdot V_\lambda(\lambda)} \quad \text{(A10)}$$

The correction factor for deviations from the nominal incident angle is given by

$$C_a = \frac{\int d\lambda \cdot S_C(\lambda) \cdot \rho_t(\theta_0,\lambda) \cdot V_\lambda(\lambda)}{\int d\lambda \cdot S_C(\lambda) \cdot \rho_s(\theta_0,\lambda) \cdot V_\lambda(\lambda)} \cdot \frac{\int d\lambda \cdot S_C(\lambda) \cdot \rho_t(\theta,\lambda) \cdot V_\lambda(\lambda)}{\int d\lambda \cdot S_C(\lambda) \cdot \rho_s(\theta,\lambda) \cdot V_\lambda(\lambda)} \quad \text{(A11)}$$

Therefore, the specular gloss for the ideal case in terms of the correction factors is given by

$$G_{t,id}(\theta_0) = G_t \cdot C_s \cdot C_p \cdot C_d \cdot C_a \quad \text{(A12)}$$

The final measurement equation, including the correction factors and the experimentally measured quantities, is given by

$$G_{t,id}(\theta_0) = 100 \cdot \frac{\rho_s(\theta_0,\lambda_D)}{\rho_0(\theta_0,\lambda_D)} \cdot \frac{\Phi_{v,s,i}}{\Phi_{v,t,i}} \cdot \frac{R_s}{R_t} \cdot \frac{N_t}{N_s} \cdot \frac{A_s}{A_t} \cdot C_s \cdot C_p \cdot C_d \cdot C_a \quad \text{(A13)}$$