Colorimetry Reference Guide
Supplemental Manual for EasyMatch®QC

The world's true measure of color
HunterLab

Hunter Associates Laboratory
11491 Sunset Hills Road
Reston, Virginia 20190 USA
www.hunterlab.com

A60-1017-674
Manual Version 1.0

Copyrights and Trademarks

Contents

Measurement Values

Color values calculated using EasyMatch QC are relative to the absolute value of a perfect reflecting diffuser as measured under the same geometric conditions, per the January 1, 1969 recommendation of the International Commission on Illumination, CIE. These values are traceable to measurements made at the National Institute of Standards and Technology.

The data types available for display within EasyMatch QC's Spectral Data Table view are described in the "Spectral Data Types" section at the end of this appendix. The remaining sections describe the color scales, color difference scales, indices, and read methods available for display in your Color Data Table view.

Color Scales and Related Color Difference Scales

CIE Tristimulus XYZ Scale

EasyMatch QC performs integration of reflectance/transmittance values over the visible spectrum to arrive at tristimulus X, Y, and Z values. These values simulate the color matching response functions of the human observer as defined by the 1931 2° Standard Observer or the 1964 CIE 10° Standard Observer (as selected). Tristimulus integrations based on the illuminants may be selected. For a complete description of how to calculate tristimulus values, refer to the publication CIE 15.2 and to ASTM Method E308.

The related color difference values are defined as follows:

$dX = X_{SMP} - X_{STD}$ $dY = Y_{SMP} - Y_{STD}$ $dZ = Z_{SMP} - Z_{STD}$.

CIE Chromaticity Coordinates, Yxy

The relationship between CIE XYZ values and the x,y chromaticity coordinates is as follows:

Y = CIE Tristimulus Y (as above) $x = \frac{X}{X+Y+Z}$ $y = \frac{Y}{X+Y+Z}$

The related color difference values are defined as follows:

$dY = Y_{SMP} - Y_{STD}$ $dx = x_{SMP} - x_{STD}$ $dy = y_{SMP} - y_{STD}$.

Opponent-Color Scales (Hunter Lab, CIE 1976 L*a*b, and CIE L*C*h)

The opponent-color scales give measurements of color in units of approximate visual uniformity throughout the color solid. Thus, in the Hunter Lab scale, L measures lightness and varies from 100 for perfect white to zero for black, approximately as the eye would evaluate it. The chromaticity dimensions (a and b) give understandable designations of color as follows: *

a measures redness when positive, gray when zero, and greenness when negative.
b measures yellowness when positive, gray when zero, and blueness when negative.

The relationship between the Hunter Lab Scale and the CIE XYZ Scale for the CIE 1931 2° Standard Observer and the CIE 1964 10° Standard Observer is as follows:

$$L = 100\sqrt{\frac{Y}{Y_n}}$$

$$a = K_a \frac{X/X_n - Y/Y_n}{\sqrt{Y/Y_n}}$$

$$b = K_b \frac{Y/Y_n - Z/Z_n}{\sqrt{Y/Y_n}}$$

Where, X, Y, and Z are the CIE tristimulus values obtained for the sample.

X_n, Y_n, and Z_n are tristimulus values of the standard illuminant as listed in ASTM E308 with Y_n always equal to 100.00 (normalized).

K_a and K_b are the expansion factors computed by the illuminant and observer used:

Illuminant **A** represents incandescent (tungsten) lamplight with an approximate color temperature of 2854 K. Illuminant **C** represents average, or north sky, daylight with a correlated color temperature of approximately 6770 K. Illuminants **D65**, **D50**, **D55**, and **D75** represent daylight with correlated color temperatures of approximately 6500 K, 5000 K, 5500 K, and 7500 K, respectively. Illuminants **F02** (cool white fluorescent), **F07**, and **F11** are fluorescent illuminants. **TL84** and **Ultra3000** are custom illuminants.

The Hunter Lab total color difference (dE) and chromaticity difference (dC) for any illuminant and observer are calculated as follows:

$$dE = \sqrt{dL^2 + da^2 + db^2}$$

$$dC = \sqrt{da^2 + db^2}$$

Where, $dL = L_{SMP} - L_{STD}$ (if + dL, sample is lighter than standard;
if - dL, sample is darker than standard.)

$da = a_{SMP} - a_{STD}$ (if + da, sample is redder than standard;
if - da, sample is greener than standard.)

$db = b_{SMP} - b_{STD}$ (if + db, sample is yellower than standard;
if - db, sample is bluer than standard.)

The dE derived from these opponent-color scales approximates the NBS Unit of Color Difference (Judd-Hunter), which represents the average maximum difference acceptable in a series of dye-house commercial matches in 1939.

The **CIE 1976 L*a*b* Scale** is recommended by the Commission Internationale de l'Eclairage (CIE). It is a simplified cube root version of the Adams-Nickerson space produced by plotting the quantities of L*a*b* in rectangular coordinates.

The relationship between the CIE L*a*b* scale and the CIE XYZ scale for any illuminant referenced in ASTM E308 is as follows:

$$L^* = 116\ f\left(\frac{Y}{Y_n}\right) - 16$$

$$a^* = 500\left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right]$$

$$b^* = 200\left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right]$$

Where, $f\left(X/X_n\right) = \sqrt[3]{X/X_n}$ if $X/X_n > (24/116)^3$

$$f\left(\frac{X}{X_n}\right) = \left(841/108\right)\left(\frac{X}{X_n}\right) + \frac{16}{116} \quad \text{if } X/X_n \le (24/116)^3$$

$$f\left(Y/Y_n\right) = \sqrt[3]{Y/Y_n} \quad \text{if } Y/Y_n > (24/116)^3$$

$$f\left(\frac{Y}{Y_n}\right) = \left(841/108\right)\left(\frac{Y}{Y_n}\right) + \frac{16}{116} \quad \text{if } Y/Y_n \le (24/116)^3$$

$$f\left(Z/Z_n\right) = \sqrt[3]{Z/Z_n} \quad \text{if } Z/Z_n > (24/116)^3$$

$$f\left(\frac{Z}{Z_n}\right) = \left(841/108\right)\left(\frac{Z}{Z_n}\right) + \frac{16}{116} \quad \text{if } Z/Z_n \le (24/116)^3$$

and X_n, Y_n, and Z_n are tristimulus values for any illuminant.

Total Difference (dE*), CIE 1976 a,b Chroma-Difference (dC*), and CIE 1976 a,b Hue Difference (dH*) are defined as follows:

$$dE^* = \sqrt{dL^{*2} + da^{*2} + db^{*2}}$$

$dC^* = C^*_{smp} - C^*_{std}$ where $C^* = \sqrt{a^{*2} + b^{*2}}$ and is termed metric chroma

$$dH^* = \sqrt{dE^{*2} - dL^{*2} - dC^{*2}}$$

Where, $dL^* = L^*_{SMP} - L^*_{STD}$

$da^* = a^*_{SMP} - a^*_{STD}$

$db^* - b^*_{SMP} - b^*_{STD}$

For more information, see AATCC Test Method 173: *Calculation of Small Color Differences*.

CIE LCh is a modification to the CIELAB scale which plots in polar coordinates rather than rectangular ones.

dC* is the difference between the chroma of the sample and the chroma of the standard, as described in a polar coordinate system.

dh* describes the difference between the hue angle (h°) of the standard and the hue angle of the sample in a polar coordinate system, where:

If h°smp > h°std then dh* is regarded as positive.
If h°std > h°smp then dh* is regarded as negative.

See "Recommendation on Uniform Color Spaces, Color Difference Equations, Psychometric Color Terms," Supplement No. 2 to *CIE Publication No. 15* (E-1.3.1) CIE, Paris, 1978.

L* = CIE 1976 psychometric lightness = $116\sqrt[3]{\frac{Y}{Y_n}} - 16$

a* = Red(+) - Green(-) axis = $500\left(\sqrt[3]{\frac{X}{X_n}} - \sqrt[3]{\frac{Y}{Y_n}}\right)$

b* = Yellow(+) - Blue(-) axis = $200\left(\sqrt[3]{\frac{Y}{Y_n}} - \sqrt[3]{\frac{Z}{Z_n}}\right)$

C^*_{ab} = CIE 1976 a,b chroma= $\sqrt{a^{*2} + b^{*2}}$

h° = CIE 1976 a,b hue-angle = arctan (b*/a*)

dh* = $h°_{Std} - h°_{Sam}$

dH^*_{ab} = CIE 1976 a,b hue-difference = $\sqrt{dE^{*2} - dL^{*2} - dC^{*2}}$

Note: Since hue angle changes dramatically for small differences in neutral and near-neutral colors, use of dH^*_{ab} hue difference is not recommended when C < 5. In this case, use dL*, da*, and db* instead to define color differences.*

dC* = Chromaticity difference in the a*b* plane = $C^*_{smp} - C^*_{std}$

dE^*_{ab} = CIE 1976 L*a*b* color difference formula = $\sqrt{dL^{*2} + da^{*2} + db^{*2}}$

d = Difference between Sample and Standard.

Reference: Commission International de l'Eclairage (CIE): "Recommendations on Uniform Color Spaces, Color Difference Equations, Psychometric Color Terms," Supplement No. 2 to *CIE Publication No. 15*, Colorimetry, Bureau Central de la CIE, Paris, 1978. For more information, see AATCC Test Method 173: *Calculation of Small Color Differences*.

Hunter RdabColor Scale

The relationship between the Hunter Rd,a,b values and the CIE XYZ values for any illuminant is as follows:

L(Rd) = Y

$$a(Rd) = K_a f(Y)\left(\frac{X}{X_n} - \frac{Y}{Y_n}\right)$$

$$b(Rd) = K_b f(Y)\left(\frac{Y}{Y_n} - \frac{Z}{Z_n}\right)$$

Where, $f(Y) = 0.51\,\frac{21 + 0.2Y}{1 + 0.2Y}$.

X, Y, and Z are the CIE tristimulus values obtained for the sample.

X_n, Y_n, and Z_n are the tristimulus values of the standard illuminant with Y_n always equal to 100.00 (normalized).

K_a and K_b are the expansion factors computed by the illuminant and observer used.

And dR Rdab = $L(Rd)_{SMP}$ - $L(Rd)_{STD}$

da Rdab = $a(Rd)_{SMP}$ - $a(Rd)_{STD}$

db Rdab - $b(Rd)_{SMP}$ - $b(Rd)_{STD}$

dE Rdab = $\sqrt{dR\,Rdab^2 + da\,Rdab^2 + db\,Rdab^2}$

$$dC\,Rdab = \sqrt{da(Rd)^2 + db(Rd)^2}$$

RxRyRz Reflection Factors

The Reflection Density Color Scale, Rx, Ry, Rz, is a variation of the CIE XYZ scale, where Rx is corrected to represent only the amber peak of the tristimulus X bi-modal response. This scale was originally developed for measurement of pulp and paper using tristimulus colorimeters. The formulas for calculating Rx, Ry, and Rz are shown below.

Rx = (100*X′/X'_{wp})

Ry = Y = 100 * Y/Y_{wp}

Rz = 100*Z/Z_{wp}

Where, X_{wp} Y_{wp} Z_{wp}= white point of perfect reflector

X'_{wp} Y'_{wp} Z'_{wp} = white point of a reflector whose reflectance is zero below 500nm and 100% at 500nm and above.

X, Y, Z = tristimulus values of the specimen

X′, Y′, Z′ = modified tristimulus values of the specimen obtained by truncating to zero the reflectance below 500nm.

Other Color Difference Scales

Elliptical Tolerancing Scales (CMC, CIE94, DIN99, and CIELAB2000)

The equation for dE CMC describes an ellipsoidal volume with axes in the direction of lightness (l), chroma (c), and hue (h) centered about a standard. When the semi-axis lengths for the dE CMC formula equal the calculated lSL, cSC, and SH values for the standard, the resulting ellipsoid describes a 1.0 dE CMC unit volume/tolerance. This volume and the size of its component parts become the basis for the establishment of an appropriately sized volume of acceptability for a given commercial situation by the application of a commercial factor (cf). The cf is the dE CMC tolerance.

When l = 2.0 and c = 1.0, the equation fixes the ratio of the three components (SL:SC:SH) to correlate with visible assessment of typical textile samples. Other values of l may be required in cases where the surface characteristics change dramatically. The value of c is always left at 1.0.

$$dE\,CMC = \sqrt{\left(\frac{dL^*}{lSL}\right)^2 + \left(\frac{dC^*}{cSC}\right)^2 + \left(\frac{dH^*}{SH}\right)^2}$$ Absolute

$$dL\,CMC = \frac{dL^*}{lSL}$$

$$dC\,CMC = \frac{dC^*}{cSC}$$

$$dH\,CMC = \frac{dH^*}{SH}$$

Where, L*, C*, and H* are those of the standard unless otherwise specified.

CMC ratio l:c. This ratio is generally 1:1 for coatings, 1.3:1 for plastics, and 2:1 for textiles. The l value may be set anywhere between 0 and 5. The l:c ratio determines the shape of the ellipsoid.

Commercial factor cf. This value is usually one to represent a just-perceptible difference, but this value may be adjusted for the industry and the product. This value may be set anywhere between 0.10 and 9.99. The commercial factor determines the size of the ellipsoid.

$$SL = \frac{0.040975L^*}{1 + 0.01765L^*}$$ for L* ≥ 16

SL = 0.511 for L* < 16

$$SC = \frac{0.0638C^*}{1 + 0.0131C^*} + 0.638$$

SH = (FT + 1 - F) SC

$$C^* = \sqrt{a^{*2} + b^{*2}}$$

$$h° = \arctan\left(\frac{b*}{a*}\right)$$

$dL^* = L^*_{SMP} - L^*_{STD}$

$dC^* = C^*_{SMP} - C^*_{STD}$

$$dH* = \sqrt{dE*^2 - dL*^2 - dC*^2}$$

$$F = \sqrt{\frac{C*^4}{C*^4 + 1900}}$$

T = 0.36 + |0.4 cos (35 + h)| if h = 164° or h > 345°

T = 0.56 + |0.2 cos (168 + h)| if 164° < h < 345°

Tolerances are:

dL* = (cf) lSL	dL* CMC = cf
dC* = (cf) cSC	dC* CMC = cf
dH* = (cf) SH	dH* CMC = cf
	dE* CMC = cf

For a more detailed description of CMC, refer to *Calculation of Small Color Differences for Acceptability*, AATCC Test Method 173-1992 published in the AATCC Technical Manual.

CIE TC 1-29

CIE TC 1-29, also called the CIE 1994 (dL CIE94 dC CIE94 dH CIE94) color difference scale, is a test scale that may eventually be approved as an official CIE scale.

dE CIE94 is the total color difference.

$$dE\,CIE94 = K_v * \left[\left(\frac{dL\,CIE94}{K_L\,S_L}\right)^2 + \left(\frac{dC\,CIE94}{K_C\,S_C}\right)^2 + \left(\frac{dH\,CIE94}{K_H\,S_H}\right)^2\right]^{1/2}$$

Where, dL CIE94, dC CIE94, and dH CIE94 are as described earlier in this section (as dL*, dC*, and dH*)

SL = 1

SC = 1 + 0.045 C*

SH = 1 + 0.015 C*.

K_L:K_C:K_H ratio. This ratio is generally 1:1:1 for coatings, 1.3:1:1 for plastics, and 2:1:1 for textiles.

DIN99

The German standards institute (DIN) developed the DIN99 standard as a new color difference formula that globally models color space using logarithms of the CIE L*a*b* coordinates rather than the linear and hyperbolic functions of CMC and CIE94. This new formula is easy to use and has equivalent performance to CMC or CIE94. It also eliminates the reference-color based distortion of CIELAB. It is calculated as follows:

Redness e = cos(16°)a* + sin(16°)b*

Yellowness f = -0.7[-sin(16°)a* + cos(16°)b*]

Chroma G = $(e^2 + f^2)^{0.5}$

Hue angle h_{ef} = arctan(f/e)

Chroma C DIN99 = $\frac{\left(\log_e\left(1+0.045G\right)\right)}{0.045k_{CH}k_E}$

Hue angle h DIN99 = $h_{ef}\frac{180}{\Pi}$

Redness a DIN99 = C DIN99 cos h_{ef}

Yellowness b DIN99 = C DIN99 sin h_{ef}

Lightness L DIN99 = 105.509 [$\log_e$ (1 + 0.0158 L*)] k_E

$$\mathrm{dE\ DIN99} = \sqrt{\left(\mathrm{dL\ DIN99}\right)^2 + \left(\mathrm{da\ DIN99}\right)^2 + \left(\mathrm{db\ DIN99}\right)^2}$$

dC DIN99 = C $\mathrm{DIN99}_{sample}$ - C $\mathrm{DIN99}_{standard}$

dH DIN99 =

$$\frac{\left(\mathrm{a\ DIN99}_{standard} * \mathrm{b\ DIN99}_{sample} - \mathrm{a\ DIN99}_{sample} * \mathrm{b\ DIN99}_{standard}\right)}{\sqrt{0.5 * \left(\mathrm{C\ DIN99}_{sample} * \mathrm{C\ DIN99}_{standard} + \mathrm{a\ DIN99}_{sample} * \mathrm{a\ DIN99}_{standard} + \mathrm{b\ DIN99}_{sample} * \mathrm{b\ DIN99}_{standard}\right)}}$$

Where: $k_E = k_{CH} = 1$ by default.

CIELAB2000

The CIELAB2000 Color Difference Equation is a ellipsoidal color difference scale similar to CMC, and is described below.

dE* 2000 is the total color difference.

$$dE*2000 = \left[\left(\frac{dL*'2000}{K_L S_L}\right)^2 + \left(\frac{dC*'2000}{K_C S_C}\right)^2 + \left(\frac{dH*'2000}{K_H S_H}\right)^2 + R_T\left(\frac{dC*'2000}{K_C S_c}\right)\left(\frac{dH*'2000}{K_L S_H}\right)\right]^{1/2}$$

Where, K_L:K_C:K_H ratio. This ratio is generally 1:1:1 for coatings, 1.3:1:1 for plastics, and 2:1:1 for textiles.

The calculation of dL*' 2000, dC*' 2000, dH*' 2000, S_L, S_C, S_H and R_T are described below.

1) Calculate $dL^{*\prime}2000, dC^{*\prime}2000, dH^{*\prime}2000$

$$C^*_{i,ab} = \sqrt{(a^*_i)^2 + (b^*_i)^2} \qquad i = 1(standard), 2(sample)$$

$$C^*_{ab} = \frac{C^*_{1,ab} + C^*_{2,ab}}{2}$$

$$G = 0.5\left(1 - \sqrt{\frac{{C^*_{ab}}^7}{{C^*_{ab}}^7 + 25^7}}\right)$$

$$a^{*\prime}_i = (1 + G) * a^*_i$$

$$C^{*\prime}_i = \sqrt{(a^{*\prime}_i)^2 + (b^*_i)^2}$$

$$h^{*\prime}_i = \begin{cases} 0 & when\ b^*_i = a^{*\prime}_i = 0 \\ \tan^{-1}(b^*_i, a^{*\prime}_i) & otherwise \end{cases}$$

$$dL^{*\prime}2000 = L^*_2 - L^*_1$$

$$dC^{*\prime}2000 = C^{*\prime}_2 - C^{*\prime}_1$$

$$dh^{*\prime} = \begin{cases} 0 & when\ C^{*\prime}_1\ C^{*\prime}_2 = 0 \\ h^{*\prime}_2 - h^{*\prime}_1 & when\ C^{*\prime}_1\ C^{*\prime}_2 \neq 0\ and\ \left|h^{*\prime}_2 - h^{*\prime}_1\right| \leq 180° \\ h^{*\prime}_2 - h^{*\prime}_1 - 360 & when\ C^{*\prime}_1\ C^{*\prime}_2 \neq 0\ and\ \left|h^{*\prime}_2 - h^{*\prime}_1\right| > 180° \\ h^{*\prime}_2 - h^{*\prime}_1 + 360 & when\ C^{*\prime}_1\ C^{*\prime}_2 \neq 0\ and\ \left|h^{*\prime}_2 - h^{*\prime}_1\right| < -180° \end{cases}$$

$$dH^{*\prime}2000 = 2\sqrt{C^{*\prime}_1\ C^{*\prime}_2}\sin\left(\frac{dh^{*\prime}}{2}\right)$$

2) Calculate S_L, S_C, S_H and R_T

$$\overline{L'} = \frac{L_2^* + L_1^*}{2}$$

$$\overline{C'} = \frac{C_2^{*\prime} + C_1^{*\prime}}{2}$$

$$\overline{h'} = \begin{cases} \dfrac{h_2^{*\prime} + h_1^{*\prime}}{2} & when\ C_1^{*'}\ C_2^{*'} \neq 0\ and\ \left|h_2^{*\prime} - h_1^{*'}\right| \leq 180° \\ \dfrac{h_2^{*\prime} + h_1^{*\prime} + 360}{2} & when\ C_1^{*'}\ C_2^{*'} \neq 0\ ,\left|h_2^{*\prime} - h_1^{*'}\right| > 180°\ and\ h_2^{*\prime} + h_1^{*'} < 360° \\ \dfrac{h_2^{*\prime} + h_1^{*\prime} - 360}{2} & when\ C_1^{*'}\ C_2^{*'} \neq 0, \left|h_2^{*\prime} - h_1^{*'}\right| > 180°\ and\ h_2^{*\prime} + h_1^{*'} \geq 360° \\ h_2^{*\prime} + h_1^{*\prime} & when\ C_1^{*\prime}\ C_2^{*\prime} = 0 \end{cases}$$

$$T = 1 - 0.17\cos\left(\overline{h'} - 30°\right) + 0.24\cos\left(2\overline{h'}\right) + 0.32\cos\left(3\overline{h'} + 6°\right) - 0.2\cos\left(4\overline{h'} - 63°\right)$$

$$S_L = 1 + \frac{0.015(\overline{L'} - 50)^2}{\sqrt{20 + (\overline{L'} - 50)^2}}$$

$$S_C = 1 + 0.045\overline{C'}$$

$$S_H = 1 + 0.015\overline{C'}T$$

$$R_C = 2\sqrt{\frac{\overline{C'}^7}{\overline{C'}^7 + 25^7}}$$

$$\Delta\Theta = 30\ exp\left[-\left(\frac{\overline{h'} - 275°}{25}\right)\right]$$

$$R_T = -\sin(2\Delta\Theta)R_C$$

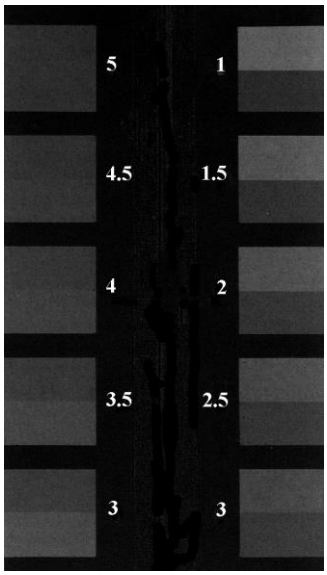
FMC-2 (Friele - MacAdam - Chickering) Color Difference

Red-green (dRedGrn FMCII) differences, yellow-blue (dYelBlu FMCII) differences, total lightness differences (dL FMCII), and total color differences (dE FMCII) between standard and sample are computed according to the Friele-MacAdam-Chickering metric (*JOSA*, February 1968, p. 292 and August 1969, p. 986).

The FMC-2 unit of color difference is based on just noticeable, or threshold, color difference data published in 1942. Friele used the data in his suggested color-difference formula, which was modified later by MacAdam, and then by Chickering. The FMC-2 Scale is a color difference scale only and was designed for Illuminant C and 2° standard observer conditions only. It has been successfully used for non-saturated colors under illuminants D65 and A as well as 10° standard observer conditions.

ISO Grey Scale

ISO Grey Scale indicates the amount of fading or color alteration that occurs with environmental exposure or washing of textiles. The loss of color using the ISO Grey Scale is evaluated by comparison to five pairs of gray standards similar to those shown below. One half of each standard is always of identical chroma to the starting specimen. The second half ranges from the starting chroma (no loss of color) to white (loss of all color). The amount of contrast between the treated and untreated fabric is related to one of the standard pairs to yield the gray scale rating. On this scale, 5 indicates that next to no color was lost, and 1 indicates that most color was lost.



The bottom half of each pair shows the starting color. The top half shows the color of the treated fabric. (Illustration from AATCC Evaluation Procedure 1.)

ISO Grey Scale, as implemented in EasyMatch QC, is based on ISO 105-A02:1993, Textiles — Tests for colour fastness — Part A02: Grey scale for assessing change in colour. It is intended as an alternative to visual assessment as described in AATCC Evaluation Procedure 1, “Gray Scale for Color Change.” It may be used in assessing any samples except those which have been treated with fluorescent whitening agents.

The ISO Grey Scale result is based on the calculations below. Some terms were further explained earlier in this chapter under “Opponent-Color Scales.”

$$dEf = \sqrt{dL^{*2} + dCf^{*2} + dHf^{*2}}$$

Where, $$dHf = \frac{dHk}{1 + \left(10C_M \,/\, 1000\right)^2}$$

$$dCf = \frac{dCk}{1 + \left(20C_M \,/\, 1000\right)^2}$$

$dHk = dH^*_{ab} - d$

$dCk = dC^*_{ab} - d$

$$d = \frac{dC^*_{ab}\, C_M\, e^{-x}}{100}$$

$$x = \left[\frac{h_M - 280}{30}\right]^2 \qquad \text{if } |h_M - 280| \le 180$$

$$x = \left[\frac{360 - |h_M - 280|}{30}\right]^2 \qquad \text{if } |h_M - 280| > 180$$

$$C_M = \frac{C_{abT} + C^*_{abO}}{2}$$

$$h_M = \frac{h_{abT} + h_{abO}}{2} \qquad \text{if } |h_{abT} - h_{abO}| \le 180$$

$$h_M = \frac{h_{abT} + h_{abO}}{2} + 180 \qquad \text{if } |h_{abT} - h_{abO}| > 180 \text{ and } |h_{abT} + h_{abO}| < 360$$

$$h_M = \frac{h_{abT} + h_{abO}}{2} - 180 \qquad \text{if } |h_{abT} - h_{abO}| > 180 \text{ and } |h_{abT} + h_{abO}| \ge 360$$

L^*_T, C^*_{abT}, h_{abT} = lightness, chroma, and hue of Test specimen

L^*_O, C^*_{abO}, h_{abO} = lightness, chroma, and hue of Original

$dL^* = L^*_T - L^*_O$

$dC^*_{ab} = C^*_{abT} - C^*_{abO}$

sign of dH^*_{ab} = sign of $(h_{abT} - h_{abO})$

$$dH^*_{ab} = \sqrt{dE^*_{ab}{}^2 - dL^{*2} - dC^*_{ab}{}^2}$$

$$dE^*_{ab} = \sqrt{dL^{*2} + da^{*2} + db^{*2}}$$

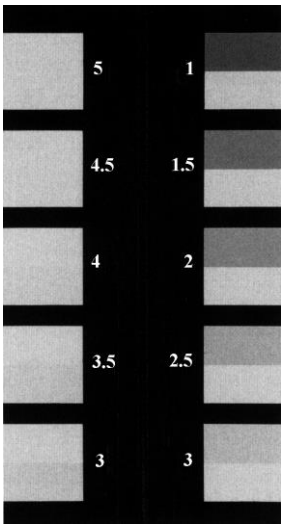
dEf is used to calculate ISO Grey Scale using the equations below:

$$\text{ISO Grey Scale} = 5 - \frac{dEf}{1.7} \qquad \text{if } dEf \leq 3.4$$

$$\text{ISO Grey Scale} = 5 - \frac{\log\left(dEf / 0.85\right)}{\log(2)} \qquad \text{if } dEf > 3.4$$

ISO Grey Stain

The transference of color from the test specimen to an adjacent specimen is evaluated in a manner very similar to that of ISO Grey Scale. Again, five standard pairs are used. One half of each standard is white, and the second half range ranges from white (no staining) to a gray with the chroma value of the test specimen (great deal of staining). A value of 5 corresponds to virtually no staining, whereas 1 indicates poor color fastness.



The bottom half of each pair shows the starting color of the adjacent fabric. The top half shows the color of the treated adjacent fabric. (Illustration from AATCC Evaluation Procedure 2).

ISO Grey Stain, as implemented in EasyMatch QC, is based on ISO 105-A04:1989, Textiles — Tests for colour fastness — Part A04: Method for the instrumental assessment of the degree of staining of adjacent fabrics. It is intended as an alternative to visual assessment as described in AATCC Evaluation Procedure 2, “Gray Scale for Staining.”

The ISO Grey Stain result is based on the calculations below.

$$dE_{GS} = dE^* - 0.4\sqrt{dE^{*2} - dL^{*2}}$$

Use dE_{GS} to calculate the SSR as follows:

ISO Grey Stain = 6.1 - 1.45 ln (dE_{GS}) for Ratings 1 to 4.

If SSR calculated by the above equation is greater than 4, recalculate using the following equation:

ISO Grey Stain = 5 - 0.23dE_{GS} for Ratings 4 to 5.

Metamerism Index

The Metamerism Index is designed to indicate the degree to which two samples which match under one illuminant no longer match under a second illuminant. The Metamerism Index feature allows the comparison of Hunter Lab values relative to operator-selectable illuminants. These values must be calculated from spectral reflectance values. The formula for deriving the index is:

$$\text{Metamerism Index} = \sqrt{(dL_{n1} - dL_{n2})^2 + (da_{n1} - da_{n2})^2 + (db_{n1} - db_{n2})^2}$$

where n1 is the 1st illuminant and n2 is the 2nd illuminant, and d = $\text{Value}_{\text{sample}}$ - $\text{Value}_{\text{standard}}$.

Strength

% Strength SUM

% Strength SUM, also known as Relative Average Strength, is calculated as follows:

$$\%\,\text{Strength SUM} = \frac{\text{Color Value SUM}_{\text{SAM}}}{\text{Color Value SUM}_{\text{STD}}} \text{x}\,100.0$$

Color Value SUM is defined in the "Indices" section of this appendix. % Strength WSUM is preferred over % Strength SUM for measurements made in reflectance.

% Strength SWL

% Strength SWL (single wavelength) is the % Strength measured at the wavelength of maximum absorbance. This is the same % Strength described in the "Spectral Data Types" section of this appendix, but at the appropriate single wavelength.

% Strength WSUM

% Strength WSUM, also known as Relative Weighted Strength, is calculated as follows:

$$\%\,\text{Strength WSUM} = \frac{\text{Color Value WSUM}_{\text{SAM}}}{\text{Color Value WSUM}_{\text{STD}}} \text{x}\,100.0$$

Color Value WSUM is defined in the "Indices" section of this appendix. % Strength SUM is preferred over % Strength WSUM for measurements made in transmission.

Indices and Related Difference Scales

a/b Ratio

a/b Ratio is simply the a of Hunter L, a, b divided by the b of Hunter L, a, b.

a/b Difference is also available, and is defined as follows:

$$da/b = (a/b)_{sample} - (a/b)_{standard.}$$

a*/b* Ratio

a*/b* Ratio is simply the a* of CIE L*a*b* divided by the b* of CIE L*a*b*.

a*/b* Difference is also available, and is defined as follows:

$$da^*/b^* = (a^*/b^*)_{sample} - (a^*/b^*)_{standard.}$$

ADMI-10 mm and ADMI-50 mm

The American Dye Manufacturer's Institute (ADMI) scale was developed for the measurement of wastewater containing dyestuffs and textile effluents. This scale may be used on clear liquids of any color.

ADMI units are based on the total dE* C/2° of APHA solutions from distilled water. Distilled water has a value of zero in ADMI units, as it does in APHA units. An ADMI value of 500 is assigned to a solution having a total color difference from distilled water equal to the total color difference from distilled water of the APHA stock solution, which has an APHA value of 500.

The HunterLab application of this scale is designed for use with bluish liquids. Be certain to use the size of transmission cell corresponding to the scale you are calculating. The sensor should be standardized in TTRAN mode using a clear liquid in that cell as a blank.

When an APHA/PtCo standard solution that conforms to ASTM D1209 is prepared and read on your instrument, it should read within the repeatability specifications of ASTM D1209. An APHA 400 solution should read as ADMI 400. ADMI values are reported in C/2° regardless of the illuminant and observer selected.

APHA is described below.

ADMI Difference is also available, and is defined as follows:

$$dADMI\text{-}10\ mm = (ADMI\text{-}10\ mm)_{sample} - (ADMI\text{-}10\ mm)_{standard,}$$

and $$dADMI\text{-}50\ mm = (dADMI\text{-}50\ mm)_{sample} - (dADMI\text{-}50\ mm)_{standard.}$$

APHA-10, -20, and -50 mm

The American Public Health Association (APHA) Index was developed in the 1890s as a visual indicator of the purity of wastewater, where color is due to the presence of naturally-occurring organic materials such as leaves, bark, roots, humus, and peat. Today, APHA is used as a metric for purity in the chemical, oil, plastics, and pharmaceutical industries. This scale serves to quantify the appearance of yellowness, a visual indicator of product degradation due to light and/or heat, the presence of impurities, and the effects of processing.

APHA-10, -20, and -50 mm are designed to yield APHA/PtCo values that closely correlate to APHA/PtCo standard solution values as defined by ASTM D1209. They are calculated from the YI E313 yellowness index (ASTM D5386) and are optimized for each instrument. This index is calculated only for the C/2° illuminant/observer combination.

A transmission cell with 10-, 20-, or 50-mm path length is required for this metric.

APHA Difference is also available, and is defined as follows:

$dAPHA\text{-}10\ mm = (APHA\text{-}10\ mm)_{sample} - (APHA\text{-}10\ mm)_{standard,}$

$dAPHA\text{-}20\ mm = (dAPHA\text{-}20\ mm)_{sample} - (dAPHA\text{-}20\ mm)_{standard.}$

And $dAPHA\text{-}50\ mm = (dAPHA\text{-}50\ mm)_{sample} - (dAPHA\text{-}50\ mm)_{standard.}$

AOCS RY

In 1962, the Journal of the American Oil Chemists Society announced this scale, “AOCS-Tintometer Scale” (or “Wesson Method,” AOCS Method Cc 13b-45), using 43 glass standards [Red (R), Yellow (Y)]. Fundamentally, it is a modification of the LOVIBOND® RYBN method—and focuses on the red and yellow colors—with no blue or neutral colors. It is noted that the red measurements of the AOCS RY do not match the red measurements of LOVIBOND® RYBN.

AOCS glass color standards:

Red Glasses: 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9
1, 2, 2.5, 3, 3.5, 4 ,5, 6, 7
7.6, 8, 9, 10, 11, 12, 16, 20

Yellow Glasses: 1, 2, 3, 4, 5, 6, 7, 8, 9
10, 15, 20, 30, 35, 40, 50, 70

At HunterLab, tristimulus color measurement (CIE, C/2, Y, x, y) is used to correlate to the visual AOCS RY color standards. In EasyMatch QC, both of cell path length and report path length are reported together with AOCS RY. You can measure oil samples in cuvette/flat cell/vials then report the AOCS RY values in 1 in or 5.25 in. In EasyMatch QC, go ***to Options > Adjust Scale Factors***, select ***AOCS RY*** and then configure the cell path length and report path length.

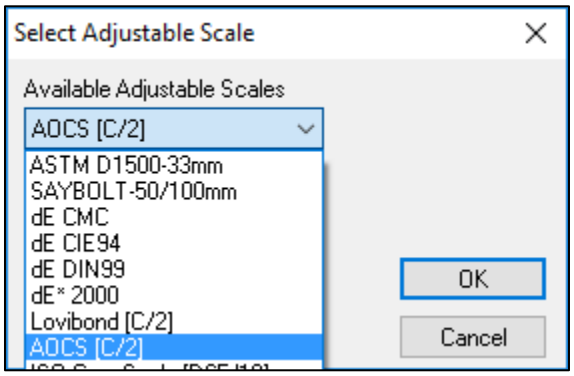


Figure 1. Selection of AOCS

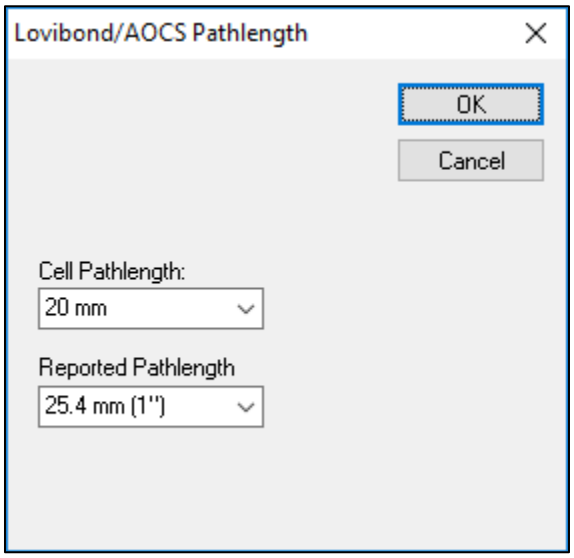


Figure 2. Pathlength

All available cell path lengths are: 10 mm, 20 mm, 25 mm, 33 mm, 50 mm. All available report path lengths are: 25.4 mm (1 in) and 133.35mm (5.25 in).

ASBC-10 mm

The American Society of Brewing Chemists (ASBC) scale is used in the measurement of the color of beer, malt worts, caramel solutions, and similarly-colored liquids. This transmission scale, which should be measured using a cell path length of 10 mm, is based on the EBC scale, which is described later in this chapter. Its range is approximately 1 to 11 units, with the more yellow, pale worts at the low end of the scale and the redder color of dark worts, beers, and caramels at the upper end of the scale. Applicable equations are given below.

$$\mathrm{ASBC} = 10 * 1.27 * \log_{10}\left(\frac{100}{T_{430\,\mathrm{nm}}}\right)$$

Where, $T_{430\,nm}$ = % transmittance at 430 nm

and

Turbidity = free (“0.0”) if $1.27 * \log_{10}\left(\frac{100}{T_{700\,nm}}\right) \leq 0.039 * 1.27 * \log_{10}\left(\frac{100}{T_{430\,nm}}\right)$, else turbid (“1.0”).

Where, $T_{700\ nm}$ = % transmittance at 700 nm.

ASBC Difference is also available, and is defined as follows:

dASBC-10 mm = $(\text{ASBC-10 mm})_{sample}$ - $(\text{ASBC-10 mm})_{standard}$.

ASTM D1500-33 mm

The ASTM D1500 scale is calculated as described below.

D1500 = 0.25 + 0.8695 (DX + DY + DZ)

Where, $DX = -\log\left(\frac{X}{98.078}\right)$

$DY = -\log\left(\frac{Y}{100.00}\right)$

if Z > 0.01, $DZ = -\log\left(\frac{Z}{118.24}\right)$

if $Z \leq 0.01$, $DZ = -\log\left(\frac{0.01}{118.24}\right)$

X is the X tristimulus value for the sample calculated for C/2° conditions

Y is the Y tristimulus value for the sample calculated for C/2° conditions

Z is the Z tristimulus value for the sample calculated for C/2° conditions.

For values greater than 8, 8 is displayed. For values less than 0, 0 is displayed.

When the D1500 function is optimized, the following equation is used:

D1500* = α + β (DX + DY + DZ)

Where, DX, DY, DZ, X, Y, and Z are as described above

α is the intercept correction constant entered by the user

β is the slope correction constant entered by the user.

To obtain the D1500 value for a specimen, complete the steps below.

1. Standardize the instrument in a transmission mode using clear liquid in a 33-mm transmission cell for setting the top of scale.
2. Select ***ASTM D1500-33 mm*** and ***ASTM D1500 Dilution Factor*** as indices for display in the Color Data Table.
3. Two columns will be added to the color data table, one for the index and another for the dilution factor.
4. To edit the scale constants, choose ***Options > Adjust Scale Factors*** and then ***ASTM D1500-33mm*** from the submenu. Click ***OK,*** edit the constants, and indicate the dilution factor as desired.
5. Measure the sample desired in a 33-mm transmission cell. The ASTM D1500-33 mm value will be displayed in that column and the dilution factor will be displayed in the ASTM D1500 Dilution Factor column.

When ASTM D1500 data is recalled, the dilution factor will be correctly displayed and the index value will be recalculated based on the current constants.

ASTM D1500 Difference is also available, and is defined as follows:

$$d\text{ASTM D1500-33 mm} = (\text{ASTM D1500-33 mm})_{sample} - (\text{ASTM D1500-33 mm})_{standard.}$$

b/a Ratio

b/a Ratio is simply the b of Hunter L, a, b divided by the a of Hunter L, a, b.

b/a Difference is also available, and is defined as follows:

$$db/a = (b/a)_{sample} - (b/a)_{standard.}$$

b*/a* Ratio

b*/a* Ratio is simply the b* of CIE L*a*b* divided by the a* of CIE L*a*b*.

b*/a* Difference is also available, and is defined as follows:

$$db^*/a^* = (b^*/a^*)_{sample} - (b^*/a^*)_{standard.}$$

Brightness 457

457 nm Brightness can be used to measure the relative brightness of paper. 457 nm brightness is calculated over the range of 400 nm to 510 nm in accordance with TAPPI document T452. While HunterLab's spectrophotometer geometries do not conform exactly to those specified by TAPPI, the measurements correlate closely with those made on TAPPI-compliant instruments.

457 nm Brightness Difference is also available, and is defined as follows:

$$d457\text{ nm Brightness} = (457\text{ nm Brightness})_{sample} - (457\text{ nm Brightness})_{standard.}$$

Color Value

Color Value is a single numerical value related to the amount of light-absorbing material (colorant) contained in a sample and is usually based on spectral data. It is most often used to calculate the difference in strength (% Strength) between a standard and a sample. Color Value may be calculated by any one of three acceptable methods. The color value which results from one method may not agree with any other method. The choice of method is usually dependent on the nature of the sample and the need to obtain a color value. The Spectrophotometric methods for obtaining color value are labeled as Color Value SUM, Color Value SWL, and Color Value WSUM, as described below.

Color Value SUM

Color Value SUM is calculated as the sum of the K/S values for the sample read across the spectrum for reflectance measurements, and from the sum of the absorbance's for the sample read across the spectrum for transmittance measurements.

$$\text{Color Value SUM} = \frac{\sum_{\lambda=1}^{\#\text{points}} \frac{K}{S\lambda}}{\#\text{points}} \qquad \text{for reflectance}$$

$$\text{Color Value SUM} = \frac{\sum_{\lambda=1}^{\#\text{points}} \text{Absorbance}_{\lambda}}{\#\text{points}} \qquad \text{for transmittance.}$$

K/S and Absorbance are described in the Spectral Data Types section of this appendix.

Color Value SUM Difference is also available, and is defined as follows:

$$d\text{Color Value SUM} = (\text{Color Value SUM})_{\text{sample}} - (\text{Color Value SUM})_{\text{standard}}.$$

Color Value SWL

Color Value SWL is the K/S measured at the wavelength of maximum absorption (minimum reflection) for reflectance measurements or the absorbance at the wavelength of maximum absorption (minimum transmittance) for transmittance measurements. K/S and Absorbance are described in the Spectral Data Types section of this appendix.

Color Value SWL Difference is also available, and is defined as follows:

dColor Value SWL = $(\text{Color Value SWL})_{\text{sample}} - (\text{Color Value SWL})_{\text{standard.}}$

Color Value WSUM

Color Value WSUM is calculated using the sum of K/S weighted by illuminant and observer for the sample read the spectrum for reflectance measurements, and using the sum of absorbances weighted by illuminant and observer for the sample read across the spectrum for transmittance measurements.

$$\text{Color Value WSUM} = \frac{\sum_{\lambda=1}^{\#\text{points}} \frac{K}{S_\lambda} * E_\lambda * S_\lambda}{\#\text{points}} \quad \text{for reflectance}$$

$$\text{Color Value WSUM} = \frac{\sum_{\lambda=1}^{\#\text{points}} \text{Absorbance}_\lambda * E_\lambda * S_\lambda}{\#\text{points}} \quad \text{for transmittance}$$

where E = Energy distribution of light source

S = Observer function.

K/S and Absorbance are described in the Spectral Data Types section of this appendix.

Color Value WSUM Difference is also available, and is defined as follows:

dColor Value WSUM = $(\text{Color Value WSUM})_{\text{sample}} - (\text{Color Value WSUM})_{\text{standard.}}$

Dominant WaveLength and Excitation Purity

The dominant wavelength and excitation purity chromaticity system was one of the first systems for specifying the chromaticity of objects other than by their x, y values. It not only compensates for the influence of the illuminant's chromaticity, but also improves the correlation between the numbers and visual attributes because it permits chromaticity specification in terms of hue and saturation. The system is based on the additive-color-mixing properties of the x,y diagram. A color is specified by describing how it would be matched by additively mixing the illuminant and light of some single wavelengths.

Dominant wavelength is the wavelength needed for mixture with the illuminant. In general, it identifies the hue of the object's color.

Excitation purity is the percentage contribution of the dominant wavelength to the mixture. Thus, 1.00 is the purity of all spectral colors and 0 is the purity of the illuminant. Excitation purity correlates with saturation.

In order to derive dominant wavelength and excitation purity for a sample, plot the position of the illuminant C - object color combination on the CIE x,y chromaticity diagram. The dominant wavelength for sample (S) under illuminant C is found by drawing a straight line from the Illuminant C point through S to the spectrum locus, where it intersects at the dominant wavelength. Excitation purity is the percentage of the distance from illuminant C to S compared to the total distance from illuminant C to the spectrum locus.

Dominant wavelength and excitation purity are calculated for the wavelengths of 397-673 nm. These values are always calculated and displayed relative to the CIE 1931 2° standard observer and CIE illuminant C regardless of the selected illuminant and observer. For complementary wavelengths, the displayed values are less than zero.

For further information see "A Digital Computer Technique for Calculation of Dominant Wavelength" by Charles G. Leete and Jack R. Lytle in *Color Engineering*, Volume 4, No. 1 (January - February 1966).

Dominant Wavelength Difference and Excitation Purity Difference are also available, and are defined as follows:

dDominant Wavelength = $(\text{Dominant Wavelength})_{\text{sample}} - (\text{Dominant Wavelength})_{\text{standard,}}$

dExcitation Purity = $(\text{Excitation Purity})_{\text{sample}} - (\text{Excitation Purity})_{\text{standard.}}$

EBC-10 mm

The European Brewing Chemists (EBC) scale is used in the measurement of color of beer, malt worts, caramel solutions, and similarly-colored liquids. The range of this transmission scale is 2 to 27 units, with yellower, pale worts at the low end and redder dark worts, beers, and caramels at the upper end. A 10-mm path length cell should be used for these measurements. EBC values are calculated as follows:

$$\text{EBC} = 25\text{f} * \log_{10}\left(\frac{100}{T_{430\text{nm}}}\right)$$

Where, f = EBC dilution factor (default = 1.0)

$T_{430\ \text{nm}}$ = measured transmittance value (%) at 430 nm

and

Turbidity = free ("0.0") if $1.27 * \log_{10}\left(\frac{100}{T_{700\text{nm}}}\right) \leq 0.039 * 1.27 * \log_{10}\left(\frac{100}{T_{430\text{nm}}}\right)$, else turbid ("1.0").

Where, $T_{700\ \text{nm}}$ = measured transmittance value (%) at 700 nm.

EBC Difference is also available, and is defined as follows:

$$dEBC\text{-}10\ mm = (EBC\text{-}10\ mm)_{sample} - (EBC\text{-}10\ mm)_{standard.}$$

EP-10 mm

EP (European Pharmacopoeia Color) is a visual liquid color index used in the pharmaceutical industry. It consists of three primary color standard solutions (yellow, red, and blue) that are combined to produce five standard color solutions: B (brown), BY (brownish-yellow), Y (yellow), GY (greenish-yellow), and R (red). These standards are then diluted with hydrochloric acid to make 37 reference EP liquid color standards: 9 Bs, 7 BYs, 7 Ys, 7 GYs, and 7 Rs.

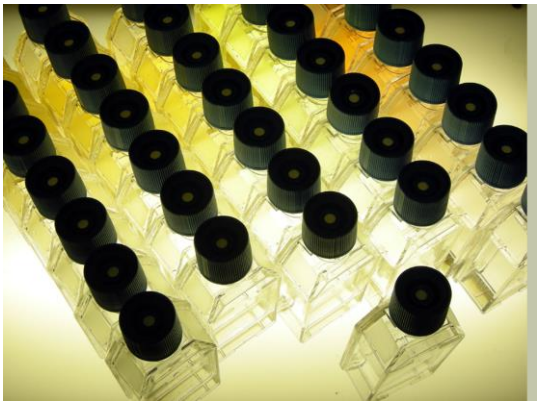


Figure 3. EP Physical Standards

A HunterLab spectrophotometer standardized in a transmission mode can be used to instrumentally determine the closest EP standard to any sample solution read. Samples should be measured using a 10-mm path length transmission cell, choosing the matching version of the EP index for display. The EP standard value (or "Water" if the sample is closest to water white) is then reported.

Refer to European Pharmacopoeia Method 2.2.2, "Degree of Coloration of Liquids," for more information.

FAC-10mm

FAC Color (AOCS Cc 13a-43), is used typically for grading dark colored oils, fats and tallows, which are too dark to be read by AOCS RY. This AOCS Cc 13a-43 method determines the color of fats and oils by comparison with permanent glass standards. FAC color is measured with 10mm path length.

At HunterLab, tristimulus color measurement (CIE C/2, L*, a*, b*) is used to correlate to the visual FAC standard glasses. Twenty-six color standards are included in FAC standard color set, numbered from 1 to 45 in odd numbers, 1, 3, 5, 7, 9, 11, 11A, 11B, 11C, 13, 15, 17, 19, 21, 23, 25, 27, 29, 31, 33, 35, 37, 39, 41, 43, and 45.

Gardner-20 mm and D6166

The Gardner indices are designed for transmission measurements of samples, such as resins, that are darker yellow or browner than those samples that would be measured with the APHA index. Samples should be measured using a 10-mm path length transmission cell for the D6166 index and a 20-mm cell for the 20-mm index.

The **Gardner-20 mm** index is a proprietary yellowness index based upon a correlation between ASTM YI E313 and Gardner Color. Gardner-20 mm Difference is also available, and is defined as follows:

$$dGardner\text{-}20\ mm = (Gardner\text{-}20\ mm)_{sample} - (Gardner\text{-}20\ mm)_{standard.}$$

The **Gardner D6166** (Gardner 10mm) index conforms to ASTM Method D6166 and uses a look-up table to determine Gardner Color based on the sample's Yxy (C/2°) values.

Table 1. Gardner D6166 Look Up Table

Gardner Color	Y	x	y
1	80	0.3177	0.3303
2	79	0.3233	0.3352
3	76	0.3329	0.3452
4	75	0.3437	0.3644
5	74	0.3558	0.3840
6	71	0.3767	0.4061
7	67	0.4044	0.4352
8	64	0.4207	0.4498
9	61	0.4343	0.4640
10	57	0.4503	0.4760
11	45	0.4842	0.4818
12	36	0.5077	0.4638
13	30	0.5392	0.4458
14	22	0.5646	0.4270
15	16	0.5857	0.4089
16	11	0.6047	0.3921
17	6	0.6290	0.3701
18	4	0.6477	0.3521

Gardner D6166 is calculated as follows:

$$G_{TM} = G_I + G_F$$

Where, G_{TM} = the Gardner color of the test material

G_I = the integer portion of the test material's Gardner color value

G_F = the fractional portion of the Gardner color value.

By comparing the x chromaticity coordinate of the test material with the x chromaticity coordinates for the D1544 visual Gardner Color standards, the integer portion of the Gardner color can be determined using this equation:

$$G_I = G_n, \text{ where } x_n \le x_{TM} < x_{n+1}$$

Where, G_n = the Gardner color value which is lighter than the test material

x_n = the x chromaticity coordinate of the Gardner color standard which is lighter than the test material

x_{TM} = the x chromaticity coordinate of the test material

x_{n+1} = the x chromaticity coordinate of the Gardner color standard which is darker than the test material.

The fractional portion of the Gardner color is calculated as follows:

$$G_F = \frac{(x_{n+1} - x_n)(x_{TM} - x_n) + (y_{n+1} - y_n)(y_{TM} - y_n)}{(x_{n+1} - x_n)^2 + (y_{n+1} - y_n)^2}$$

Where, y_n = the y chromaticity coordinate of the Gardner color standard which is lighter than the test material

y_{TM} = the y chromaticity coordinate of the test material

y_{n+1} = the y chromaticity of the Gardner color standard which is darker than the test material

x_n, x_{n+1}, and x_{TM} are as defined above.

Available values range from 0.1 to 18.0 for both Gardner scales. A value of zero or 18.1 indicates the value is out of range.

Gardner D6166 Difference is also available, and is defined as follows:

$dGardner\ D6166 = (Gardner\ D6166)_{sample} - (Gardner\ D6166)_{standard.}$

Iodine-10 mm

Iodine Color (DIN6162) is used typically for oils and chemicals ranging from yellow to brown. DIN6162 defines the iodine color value as mg iodine per 100 mL potassium iodide solution. Color matching with the iodine color scale determines the depth of color of clear liquids like solvents, plasticizers, resins, oils and fatty acids, whose color is like that of a solution of iodine and potassium iodide of the same thickness.

A HunterLab spectrophotometer standardized in a transmission mode can be used to instrumentally determine the closet Iodine standard to any sample solution. Iodine color is measured with 10 mm path length. The color range of Iodine 10 mm is 0-500 (mg/100ml). Per DIN-ISO 6271, for iodine color values of less than or approximately 1, the determination of APHA value is to be preferred.

LOVIBOND RY

The calculation of the LOVIBOND® color values is derived from the methods AOCS Cc 13e-92. We only report LOVIBOND® RY scales because for most oils and fats the color is red and yellow with LOVIBOND® B as 0. 84 glasses (Red, Yellow, Blue, and Neutral) are used in LOVIBOND® RYBN scale to compare the color of light which is either transmitted through, or reflected from, the sample. It is noted that the red measurements of the AOCS RY do not match the red measurements of LOVIBOND® RYBN.

LOVIBOND® glass color standards:

Red Glasses: 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9
1, 2, 3, 4, 5, 6, 7, 8, 9,
10, 20, 30, 40, 50, 60, 70

Yellow Glasses: 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9
1, 2, 3, 4, 5, 6, 7, 8, 9
10, 20, 30, 40, 50, 60, 70

Blue Glasses: 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9
1, 2, 3, 4, 5, 6, 7, 8, 9
10, 20, 30, 40

Neutral Glasses: 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9
1, 2, 3

At HunterLab, tristimulus color measurement (CIE, C/2, Y, x, y) is used to correlate to the visual LOVIBOND® RY color standards. In EasyMatch QC, both of cell path length and report path length are reported together with LOVIBOND® RY. You can measure oil samples in cuvette/flat cell/vials then report the LOVIBOND® RY values in 1 in or 5.25 in. In EasyMatch QC, go to ***Options >Adjust Scale Factors***, select ***LOVIBOND® RY*** and then configure the cell path length and report path length.

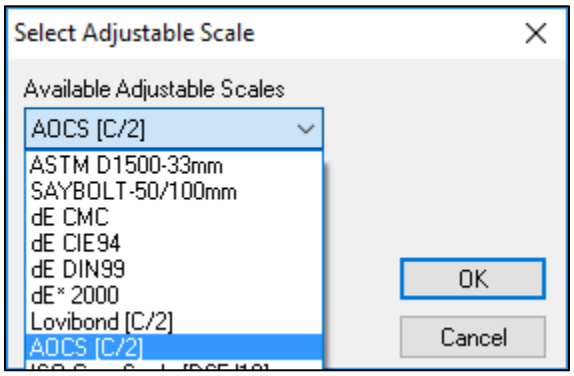


Figure 4. LOVIBOND® Scale Selection

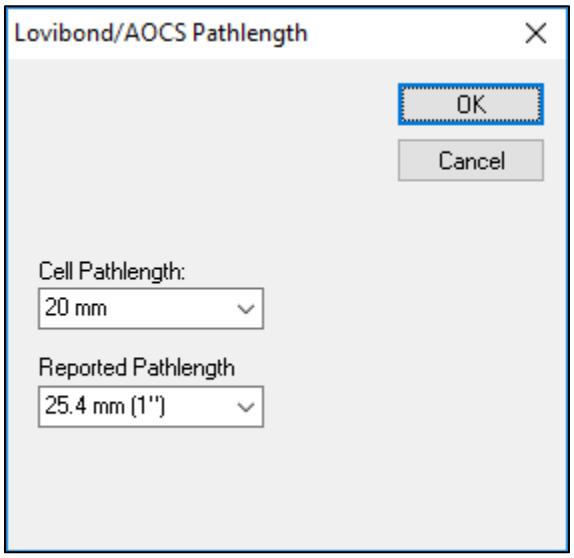


Figure 5. Select Pathlength

All available cell path lengths are: 10 mm, 20 mm, 25 mm, 33 mm, 50 mm. All available report path lengths are: 25.4 mm (1 in) and 133.35 mm (5.25 in).

Saybolt-50/100 mm

The Saybolt index is calculated as described below. These calculations adjust the spectral data to account for use of a 50 mm sample cell rather than a 100-mm cell, so spectral data must be available for this type of calculation.

$$\text{Saybolt} = 51.1 + \left(\frac{44.5}{\log_{10}\Delta E^{*} - 2.55} \right)$$

Where, $\Delta E^{*} = \sqrt{(100 - L^{*})^{2} + a^{*2} + b^{*2}}$

L* is the L* value for the sample calculated for C/2° conditions

a* is the a* value for the sample calculated for C/2° conditions

b* is the b* value for the sample calculated for C/2° conditions.

The implied standard for the DE* calculation is the top-of-scale standardization to a 100-mm cell filled with dodecane. An adjustment is also made for calculating this value using a 50-mm cell rather than a 100-mm cell.

For values greater than 30, 30 is displayed. For values less than -16, -16 is displayed.

When the Saybolt function is optimized, the following equation is used:

$$\text{Saybolt}^* = \alpha + \left(\frac{\beta}{\log_{10} \Delta E^* - \theta} \right), \text{ where}$$

ΔE^* is as above.

α is the intercept correction constant entered by the user.

β is the slope correction constant entered by the user.

θ is the correction constant entered by the user..

To obtain Saybolt values, complete the following steps.

1. Standardize the instrument in a transmission mode.
2. Select Saybolt as an index for display in the Color Data Table.
3. Two columns will be added to the color data table. The first column gives the calculated value for the index and the second column indicates “Dil” if the specimen read was diluted.
4. To edit the scale constants, choose ***Options > Configure Scales*** and ***Saybolt-50/100 mm*** from the submenu. Edit the constants and whether dilution was used.
5. The column header is displayed with a trailing asterisk (*) if custom constants are in use.
6. Read the sample using a 50 mm transmission cell.

When Saybolt data is recalled, the dilution indication will be correctly displayed and the index value will be recalculated based on the current constants. Saybolt Difference is also available, and is defined as follows:

$$\text{dSaybolt-50/100 mm} = (\text{Saybolt-50/100 mm})_{\text{sample}} - (\text{Saybolt-50/100 mm})_{\text{standard.}}$$

Tint Indices

Three tint indices are available in EasyMatch QC as defined below. These indices are available only when the instrument is standardized in a reflectance mode.

CIE Tint and ASTM E313 Tint are calculated using the same equation, given below, but are available for different illuminant/observer combinations, as described below. Refer to *CIE Publication 15.2*, “Colorimetry,” for more information on CIE Tint. Refer to *ASTM E313,* “Standard Practice for

Calculating Yellowness and Whiteness Indices from Instrumentally Measured Color Coordinates," for more information on ASTM E313 Tint.

$$\text{Tint E313} = T_x\,(x_n - x) - 650\,(y_n - y) = \text{Tint CIE}$$

where x and y are the chromaticity coordinates of the specimen and x_n and y_n are the chromaticity coordinates for the CIE standard illuminant and source used. These values are provided in the table below based on the illuminant and observer used. The T_x coefficient is also given in the table. CIE Tint is available for the D65/10°, D65/2°, and C/2° illuminant/observer combinations. ASTM E313 Tint is available for illuminants C, D50, and D65 and the 2° and 10° standard observers. A blank cell is received when any other illuminant/observer combination is in use.

Table 2. CIE Tint Coefficients

Value	C/2°	D50/2°	D65/2°	C/10°	D50/10°	D65/10°
T_x	1000	1000	1000	900	900	900
x_n	0.3101	0.3457	0.3127	0.3104	0.3477	0.3138
y_n	0.3161	0.3585	0.3290	0.3191	0.3595	0.3310

Tint CIE Difference and Tint E313 Difference are also available, and are defined as follows:

dTint CIE = $(\text{Tint CIE})_{\text{sample}} - (\text{Tint CIE})_{\text{standard}}$,

dTint E313 = $(\text{Tint E313})_{\text{sample}} - (\text{Tint E313})_{\text{standard}}$.

Tint GANZ = mx + ny + k

Where, $m = \dfrac{-\cos(\alpha)}{BW} = -937.588$

$n = \dfrac{\sin(\alpha)}{BW} = 826.697$

$k = -m\bar{x} - n\bar{y} = 21.352$

x and y are the CIE chromaticity coordinates.

α is the angle, in chromaticity space, between the x chromaticity axis and the line that joins the chromaticity coordinates measured for the lowest and highest whiteness steps of the 4-step cotton white scale. Its value depends on the exact illumination conditions of the instrument.

Note: Only the LabScan XE, UltraScan PRO, and UltraScan VIS instruments with the UV control option installed may correctly calculate Ganz Tint.

Tint GANZ Difference is also available, and is defined as follows:

$$dTint\ GANZ = (Tint\ GANZ)_{sample} - (Tint\ GANZ)_{standard.}$$

A few caveats regarding measurement of tint:

- The application of this equation is restricted to samples that are called “white” commercially, that are similar in color and fluorescence, and that are measured on the same instrument at the same time. Under these conditions, their use should give relative, but not absolute, evaluations of tint that are adequate for commercial use.
- The more positive the value of tint, the greater is the indicated greenish tint of the sample. The more negative the value of tint, the greater is its reddish tint. Lines of equal tint are approximately parallel to the line of dominant wavelength 466 nm. For perfect white, tint = 0.
- Equal differences in tint do not always represent equal perceptual differences in tint.
- This equation should only be used for samples having tint values between -3 and +3.

USP 10-mm

USP (United States Pharmacopeia Color) is a visual liquid color index used in the pharmaceutical industry. It consists of three primary color standard solutions (cobaltous chloride, ferric chloride, and cupric sulfate) that are combined with water to produce 20 reference USP liquid color standards labeled A-T.

Figure 6. USP Standards

A HunterLab spectrophotometer standardized in a transmission mode may be used to instrumentally determine the closest USP standard to any sample solution read. Samples should be measured using a 10-mm path length transmission cell, choosing the matching version of the USP index for display. The USP standard value (or “Water” if the sample is closest to water white) is then reported.

Refer to U.S. Pharmacopeia Monograph 631, “Color and Achromicity,” for more information.

Whiteness Indices

Whiteness is associated with a region or volume in color space in which objects are recognized as white. Degree of whiteness is measured by the degree of departure of the object from a perfect white.

Whiteness Index per CIE is equivalent to the whiteness index published in **ASTM Method E313**.

$$WI\ CIE = Y + 800\ (x_n - x) + 1700\ (y_n - y) = WI\ E313$$

where Y, x, y are the luminance factor and chromaticity coordinates of the specimen, and x_n and y_n are the chromaticity coordinates for the CIE standard illuminant and source used. These values are provided in the table below based on the illuminant and observer used. Whiteness Index can only be calculated for illuminants C, D50, and D65. A blank cell is received when any other illuminant is in use.

Table 3. Coefficients for Xn and Yn by Ill/Obs

Value	C/2°	D50/2°	D65/2°	C/10°	D50/10°	D65/10°
x_n	0.3101	0.3457	0.3127	0.3104	0.3477	0.3138
y_n	0.3161	0.3585	0.3290	0.3191	0.3595	0.3310

Refer to ASTM Method E313, "Standard Practice for Calculating Yellowness and Whiteness Indices from Instrumentally Measured Color Coordinates," for more information.

Whiteness Index per the CIE Colorimetry Committee (displayed as Whiteness Index CIE) is the same as the current ASTM E313 whiteness described above, but may only be calculated and displayed for D65/2°, D65/10°, and C/2°. The CIE method on which this index is based is equivalent to AATCC Test Method 110: Whiteness of Textiles.

WI CIE Difference and WI E313 Difference are also available, and are defined as follows:

$$dWI\ CIE = (WI\ CIE)_{sample} - (WI\ CIE)_{standard,}$$

$$dWI\ E313 = (WI\ E313)_{sample} - (WI\ E313)_{standard.}$$

Spectral reflectance can vary based on the geometry of the instrument used, the exact properties of the illuminant simulated (usually D65), and the condition of the instrument's lamp. This can be a problem, especially for measurement of fluorescent samples, where maintenance of a constant illuminant spectral energy distribution is imperative. The main purpose in creating the **Ganz Whiteness Index** was to allow constant, comparable results for whiteness and tint of fluorescent materials, even by using instruments of different designs and different illuminant simulation.

$$WI\ GANZ = DY + Px + Qy + C \text{ for D65/10°}$$

Where, $D = \frac{\delta W}{\delta Y} = 1$

$P = \left(\frac{-\delta W}{\delta S}\right) * \left(\frac{\cos(\varphi + \eta)}{\cos(\varphi)}\right)$ = -1868.113 for UltraScan VIS

= a similar value, optimized for each individual instrument for ColorQuest XE, LabScan XE, UltraScan PRO, and Vista

$$Q = \left(\frac{\delta W}{\delta S}\right) * \left(\frac{\sin(\varphi + \pi)}{\cos(\varphi)}\right)$$ = -3695.281 for UltraScan VIS

= a similar value, optimized for each individual instrument for ColorQuest XE, LabScan XE, UltraScan PRO, and Vista

$$C = \left[W_0 * \left(1 - \frac{\delta W}{\delta Y}\right)\right] - \left(P_{X_n}\right) - \left(Q_{y_n}\right)$$ = 1811.033 for UltraScan VIS

= a similar value, optimized for each individual instrument for ColorQuest XE, LabScan XE, UltraScan PRO, and Vista.

Y, x, and y are the CIE Chromaticity Coordinates

φ = the hue preference in reference to the perpendicular to the reference dominant wavelength (RWL) = 15°

η = the angle between the RWL and the x-axis of the chromaticity chart = 48.18154°

$\frac{\delta W}{\delta Y} = 1$ = contribution of lightness to whiteness

$\frac{\delta W}{\delta S} = 4000$ = contribution of saturation to whiteness

W_0 = 100 = degree of whiteness of physical ideal white

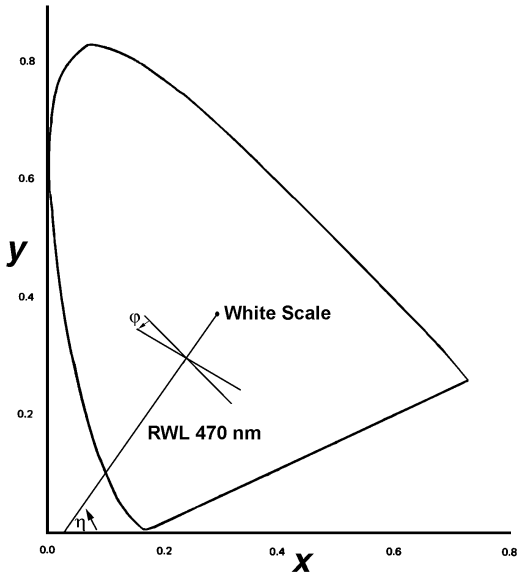
$$x_n = \frac{X_n}{(X_n + Y_n + Z_n)} = 0.313795$$

$$y_n = \frac{Y_n}{(X_n + Y_n + Z_n)} = 0.330972$$

X_n = 94.81 (for D65/10°)

Y_n = 100 (for D65/10°)

Z_n = 107.33 (for D65/10°).



Note: Only the ColorQuest XE, LabScan XE, UltraScan PRO, and UltraScan VIS instruments with the UV control option installed may correctly calculate Ganz Whiteness.

Information from Griesser, Rolf, "Assessment of Whiteness and Tint of Fluorescent Substrates with Good Inter-instrument Correlation," *Color Research and Application*, Vol. 19, 1994.

WI GANZ Difference is also available, and is defined as follows:

$$dWI\ GANZ = (WI\ GANZ)_{sample} - (WI\ GANZ)_{standard.}$$

Y Brightness

Y brightness is the Y value from the CIE XYZ color scale.

Y Brightness Difference is also available, and is defined as follows:

$$dY\ Brightness = (Y\ Brightness)_{sample} - (Y\ Brightness)_{standard.}$$

Yellowness Indices

Visually, yellowness is associated with scorching, soiling, and general product degradation by light, chemical exposure, and processing. Yellowness indices are used chiefly to measure these types of degradation.

Yellowness Index per ASTM Method E313 is calculated as follows:

$$YI\ E313 = \frac{100\left(C_x X - C_Z Z\right)}{Y}$$

where X, Y, and Z are the CIE Tristimulus values and the coefficients depend on the illuminant and observer as indicated in the table below. Yellowness Index may only be calculated for illuminants D65 and C. A blank cell is received when any other illuminant is in use.

Table 4. Yellowness Coefficients

Coefficient	C/2°	D65/2°	C/10°	D65/10°
C_X	1.2769	1.2985	1.2871	1.3013
C_Z	1.0592	1.1335	1.0781	1.1498

YI E313 Difference is also available, and is defined as follows:

$dYI\ E313 = (YI\ E313)_{sample} - (YI\ E313)_{standard.}$

Yellowness Index per ASTM Method D1925 is calculated by the software as follows:

$$YI\ D1925 = \frac{100\left(1.27497679\,5X - 1.05839817\,8\,Z\right)}{Y}$$ under C/2° conditions for all instruments.

The yellowness index formula is shown in ASTM D1925 as:

$$YI\ D1925 = \frac{100\left(1.28\,X_{CIE} - 1.06\,Z_{CIE}\right)}{Y_{CIE}}$$ under C/2° conditions.

The tristimulus values of clear air (for CIE illuminant C and the 1931 CIE 2° standard observer) are X = 98.041, Y = 100.000, Z = 118.103. Using these values, the ASTM formula yields YI = 0.303 for clear air because the factors are truncated to three significant figures. In order to set the yellowness index for air equal to 0.0, the constant multipliers for X_{CIE} and Z_{CIE} have been expanded slightly.

The ASTM D1925 method was withdrawn in 1995, but this formula still provides useful information. This index is always calculated for C/2°, regardless what illuminant and observer are chosen.

YI D1925 Difference is also available, and is defined as follows:

$dYI\ D1925 = (YI\ D1925)_{sample} - (YI\ D1925)_{standard.}$

Paper Brightness (Z%)

Paper brightness, Z%, is used in the evaluation of the degradation of white materials. It can also be a measure of the effectiveness of bleaching.

$$Z\% = \frac{100Z_{CIE}}{Z_n}.$$

Z% Difference is also available, and is defined as follows: $dZ\% = (Z\%)_{sample} - (Z\%)_{standard.}$

Read Methods

Haze

A transmission haze measurement is a ratio of the diffuse light to the total light transmitted by a specimen. Useful measurements of haze can be made on the HunterLab instruments listed below, although the results do not conform exactly to ASTM method D1003 because of differences in instrument geometry. Haze is calculated as follows:

$$\text{Haze} = \frac{Y_{\text{Diffuse Transmission}}}{Y_{\text{Total Transmission}}} \text{ x } 100 \text{ .}$$

Haze measurements can be made only in a transmission mode on a benchtop sphere instrument (ColorQuest XE, UltraScan PRO, Vista, or UltraScan VIS).

In order to measure and display haze values using EasyMatch QC, follow the steps outlined below:

1. Select ***Options > Read Method***.

2. Select ***Haze*** from the dialog box that appears. The screen changes to allow additional options.

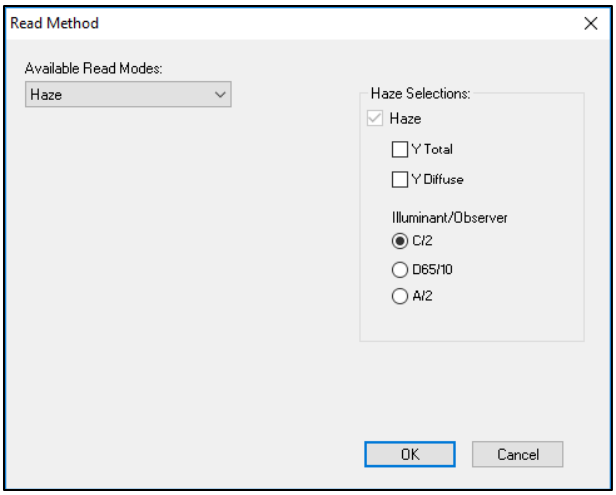


Figure 7. Options > Read Method

3. Haze is automatically selected for display in your Color Data Table. Check the boxes next to Y Total and/or Y Diffuse to also show these components of the haze calculation. Click the radio button next to the illuminant/observer combination you wish to use. Then click ***OK***.

4. Standardize the instrument in TTRAN mode. This is a 3 step process on all instruments, but the Vista. With Vista, the standardization is automated. First, place the black card at the lens side. Then, remove the black card and place the white tile at the reflectance port. Finally, remove the white tile and place the light trap at the reflectance port.

5. Read the standard or sample by choosing ***Read Standard*** or ***Read Sample*** from the ***Measurements*** menu, clicking the ***Read Standard*** or ***Read Sample*** button on the toolbar, or pressing ***F2*** or ***F3***. The following prompt appears.

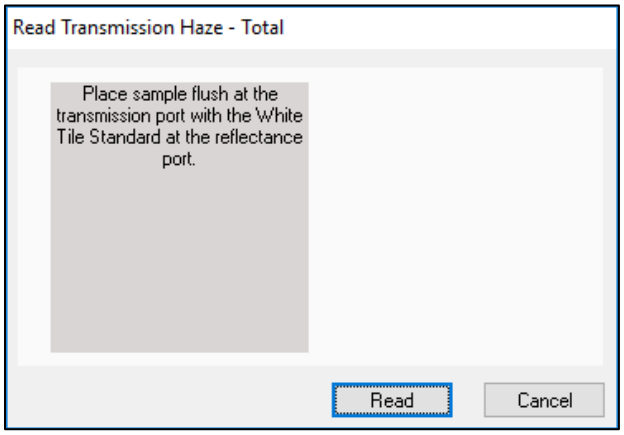


Figure 8. Read Sample with White Tile in Place

6. Place your sample against the transmission port (the hole in the sphere inside the transmission compartment) and place the white calibration tile at the reflectance port. Click ***Read***. The instrument reads and then the following prompt appears.

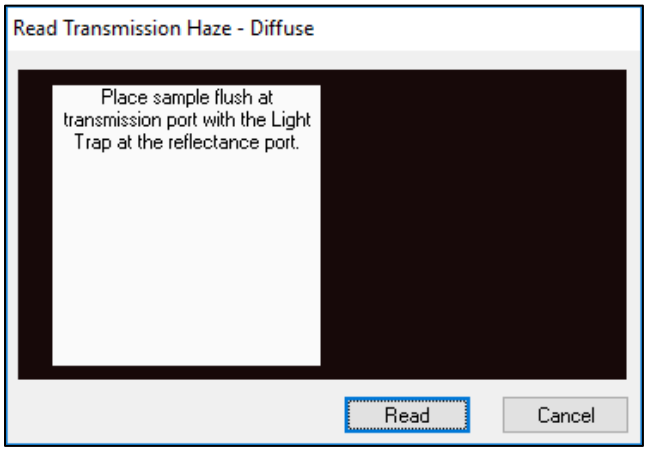


Figure 9. Read Sample with Light Trap at Port

7. Leave your sample at the transmission port and replace the white calibration tile with the light trap. Click ***Read***. The instrument reads. You may be prompted to enter an ID for the measurement as usual. After you do so, Haze and the other parameters you chose to display will be shown in your Color Data Table.

ID	L*	a*	b*	Haze % C/2	Y Total C/2	Y Diffuse C/2
Haze sample	94.96	0.00	2.88	10.78	87.73	9.46

Figure 10. Haze Results

NTU-10 mm (Opalescence/Turbidity of Liquids

Opalescence/Turbidity of liquids is not a common colorimetric application, though one application encountered is measuring the opalescence of the bleaching solutions used in dental whitening. Opalescence/Turbidity is always reported with this unit, NTU (nephelometric turbidity units).

NTU-10 mm index has been implemented into our software to report the degree of Opalescence/Turbidity of liquids. It is calculated from transmittance Haze. You can measure NTU-10 mm using a sphere instrument such as Vista, UltraScan PRO, or UltraScan VIS.

Opacity

Note: Opacity may not be measured using a ColorQuest XT or Vista.

Opacity measurements determine opacity (in reflectance mode) by a contrast ratio measurement. The Y value of the specimen backed by the black glass, non-slip (black) pad for the sample clamp, or light trap is divided by the Y value of the specimen backed by the white tile or white sample clamp insert. The resulting fraction is Y%, or opacity, which is calculated as follows:

$$\text{Opacity} = \frac{Y_{\text{Black Backing}}}{Y_{\text{WhiteBacking}}} \text{ x } 100 \, .$$

In order to measure and display opacity values, follow the steps outlined below:

1. Select ***Options > Read Method***.
2. Select ***Opacity*** from the dialog box that appears. The screen changes to allow additional options.

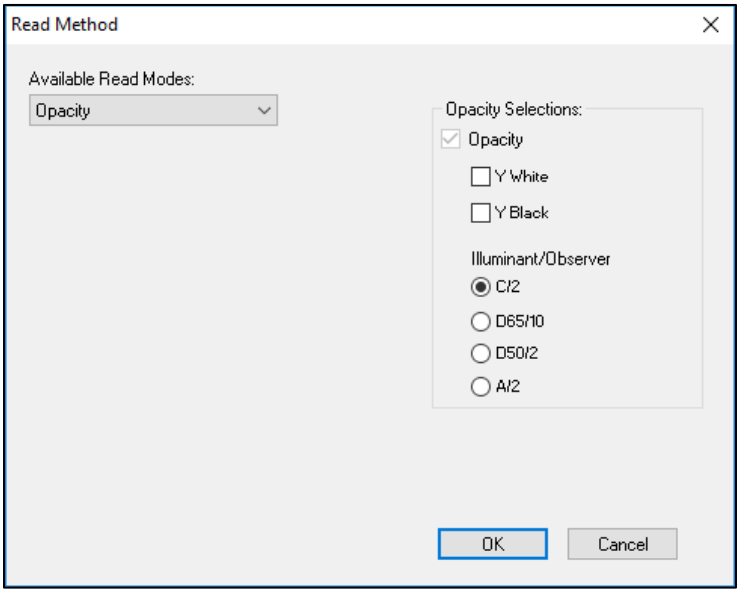


Figure 11. Read Method for Opacity

3. Opacity is automatically selected for display in your Color Data Table. Check the boxes next to Y White and/or Y Black to also show these components of the opacity

calculation. Click the radio button next to the illuminant/observer combination you wish to use. Then click ***OK***.

4. Standardize the instrument. (Use RSIN mode for UltraScan PRO and UltraScan VIS.)
5. Read the standard or sample by choosing ***Read Standard*** or ***Read Sample*** from the ***Measurements*** menu, clicking the ***Read Standard*** or ***Read Sample*** button on the toolbar, or pressing ***F2*** or ***F3***. The following prompt appears.

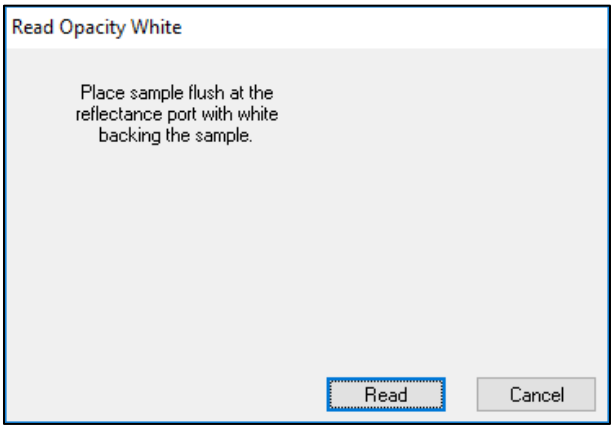


Figure 12. Read Opacity with White Backing

6. Place your sample at the measurement port, backing it with the white standard tile or the white disk of the sample clamp. Click ***Read***. The instrument reads and then the following prompt appears.

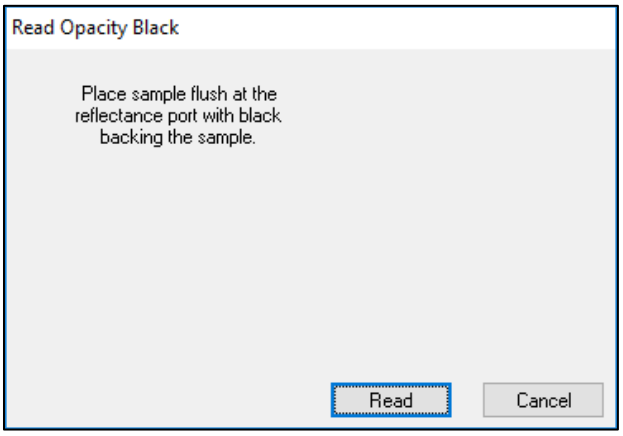


Figure 13. Read Opacity with Black Backing

7. Remove the white backing and place the sample at the measurement port, backing it with the black glass, light trap, or the black non-slip pad of the sample clamp. Click ***Read***. The instrument reads. You may be prompted to enter an ID for the measurement as usual. After you do so, Haze and the other parameters you chose to display will be shown in your Color Data Table.

ID	L*	a*	b*	Opacity Y C/2
Sample 19	57.72	-21.99	10.38	22.9

Figure 14. Opacity Results

Spectral Data Types

% Strength

Selecting % Strength as a difference data type for display in the Spectral Data Table results in the display of % Strength values for samples as compared to a standard. % Strength is calculated separately for each wavelength displayed, as follows:

$$\%\,\text{Strength} = \frac{\text{K/S}_{\text{sample}}}{\text{K/S}_{\text{standard}}} * 100 \qquad \text{for reflectance}$$

$$\%\,\text{Strength} = \frac{\text{Absorbance}_{\text{sample}}}{\text{Absorbance}_{\text{standard}}} * 100 \quad \text{for transmittance.}$$

K/S and Absorbance are described below.

Absorbance

Selecting Absorbance as the spectral data type when configuring a Spectral Data Table for an instrument standardized in Total or Regular Transmittance results in the display of absorbance values. Absorbance values are calculated for each wavelength.

Absorbance = $-\log_{10}T$, where T = % transmittance.

In the Color Data Table configuration, a wavelength range appropriate for your instrument should be chosen. Do not choose wavelengths above or below the range of your instrument or the results of these calculations may be in error.

K/S

Selecting K/S as the spectral data type when configuring the Spectral Data Table results in the display of K/S values. These values are valid only for measurements made in a reflectance mode. Therefore, they are displayed only when the standardization mode is reflectance.

K/S values for the product standard and sample are calculated for each wavelength. The points of minimum and maximum reflectance of the product standard and sample may be viewed on the Spectral Plot.

$$\frac{\text{K}}{\text{S}} = \frac{\left[1 - 0.01\,\text{R}\right]^2}{2\left[0.01\text{R}\right]}$$, where R = % reflectance.

Calculating K/S is only appropriate for samples whose minimum % reflectance (at any wavelength) is at least 10%. If the minimum % reflectance is less than 10%, you should dilute the sample before measurement of K/S.

In the Spectral Data Table configuration, a wavelength range appropriate for your instrument should be chosen. Do not choose wavelengths above or below the range of your instrument or the results of these calculations may be in error.

Reflectance

Selecting reflectance spectral data allows the raw reflectance value (%) for each wavelength interval selected in the configuration to be displayed.

Transmittance

Selecting transmittance spectral data allows the raw transmittance value (%) for each wavelength interval selected in the configuration to be displayed.

Index