



society of dyers
and colourists



Assessment of the Performance of a Colour Measurement Instrument

Colour Measurement Committee

ISSUE 1: 2011

Working Group Members:

Mike Pointer
Peter Clarke
Andrew Filarowski
Christine Holdstock
Ronnier Luo
Chris Williamson
Roy Choudhury



A Chartered Society
since 1963

Assessment of the Performance of a Colour Measurement Instrument

1. SCOPE

Many laboratory managers assume that a colour-measuring instrument will work in a consistent way over a period of many years with little or no maintenance. In addition, it is often assumed that each measurement is 'perfect' and not subject to any variation measurement due to extraneous circumstances.

This best practice guide provides a number of procedures that can be used to assess the performance of an instrument that is used for the measurement of surface colour. It is implicitly assumed that this instrument is a spectrophotometer, and the examples given are based on such an instrument. The concepts however, are equally applicable to other colour measurement instruments, for example, tristimulus colorimeters, camera-based imaging colorimeters, or spectroradiometers. The concepts can also be applied to instruments that are designed to measure the colour of transmitting materials.

The guide considers the performance in terms of the uncertainty in the measurements. These uncertainties are themselves considered in terms of repeatability or precision, and reproducibility or accuracy. By precision, is meant the consistency with which measurements can be made of the same sample. By accuracy is meant the degree to which measurements of a sample agree with those made by a standard instrument or procedure in which all possible errors are minimized.

While these can be considered the main contributions to the uncertainty in any measurement, a number of other likely contributors are also described, together with reference to the literature where their assessment is described.

2. HEALTH AND SAFETY

This best practice guide does not address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this guide to establish appropriate practices that comply with any specific health and safety regulation.

3. INTRODUCTION

Manufacturing industries survive on measurement and the dye and textile industries are no exception. The customer sets a specification, the manufacturer produces a product to that specification, and the customer has an expectation that the product will comply to their requirements. The quality of this manufacturing process can only be assessed by measurement; but how good is that measurement? Very often, a repeat measurement of the same sample gives a different result; a measurement made by a different person on a different, but similar, instrument, perhaps at a different location, gives a different result.

Whilst modern colour measurement instruments usually have acceptable performance when first manufactured, this performance can degrade with time or with changes in the operating environment, and variations can also occur when the instrument is moved. The performance of the instrument therefore should be monitored over time.

How can this variability be rationalised in order that the manufacturer and customer can have some confidence that the product specification has been met? The answer might be thought to lie in the numbers quoted in the instrument manufacturer's specification. These however, are based on the measurement of a specific, often white, sample and while useful, do not give a complete picture of the likely measurement variability. The best answer lies in understanding the uncertainty associated with the measurements

made using any relevant instrument that contribute to the monitoring of any manufacturing process.

Measurement uncertainty

An uncertainty is a figure of merit associated with the actual measured value; the boundary limits within which the 'true' value lies. An uncertainty budget is a table that lists all of the uncertainties associated with the measurement, together with a figure that is derived by combining them.

Precision and accuracy

Precision is affected by random errors and the most common sources of these random errors in colour measurement instruments are electronic noise, variations in sensitivity, and sample preparation and presentation. Accuracy is affected by systematic errors and common sources of these are wavelength calibration, detector linearity, geometry of illumination and viewing, and polarization. Systematic errors may also be associated with stray light, *wavelength* scale, wavelength bandwidth, reference-white calibration, *thermochromism*, and *fluorescence*.

Calibration standards

The absolute accuracy of a measurement can be equated to the total uncertainty in that measurement, and can only be determined by use of a set of calibration standards, usually measured by a national standardising laboratory using the best possible instrumentation and procedures, and supplied with a certificate that includes an estimate of their associated measurement uncertainty.

A set of twelve calibrated reflecting ceramic tiles is produced by CERAM and is available in the UK with calibration from either CERAM or the National Physical Laboratory (NPL), Fig. 1. In the USA calibration is available from the National Institute of Standards and Technology (NIST). While this set of tiles is available with both gloss and matt surfaces, and includes three grey tiles of different *spectral reflectances*, it does not include a white tile and a black tile: these are available separately. Alternative reference standards include those made using Spectralon® and Fluorilon® and these are available from Labsphere and Avian Technologies respectively.



Fig. 1. The set of twelve calibrated reflecting ceramic tiles is produced by CERAM®

Calibration

In the United Kingdom, calibration of reflectance colour standards is only possible at laboratories that have ISO/IEC 17025 accreditation from UKAS – the United Kingdom

Accreditation Service, and to date, there are only two such laboratories: the National Physical Laboratory and CERAM.

While CERAM Colour Standards are durable and very stable, it is recommended that they be recalibrated after a period of no more than five years to maintain accuracy of measurement. If any of the standards become damaged or permanently soiled before this time, the certificated values will not be valid and recalibration or replacement with a new standard is necessary.

Appropriate certificates are supplied for each calibration standard by the ISO/IEC 17025 accredited laboratory according to customer specification. For colorimetric applications, this should include some or all of the following:

- spectral measurement from 380 nm to 780 nm in steps of 5 nm or 10 nm,
- for $d:8^\circ$ or $8^\circ:d$, specular included and/or specular excluded geometry,
- for $0^\circ:45^\circ$ or $45^\circ:0^\circ$ geometry,
- CIE X, Y, Z tristimulus values,
- CIE x, y and/or u', v' chromaticity coordinates
- CIELAB $L^*, a^*, b^*, C_{ab}^*, h_{ab}$ coordinates,
- all calculated using CIE Standard Illuminants D65 and SA, for the CIE 2° and/or 10° Standard Colorimetric Observers as appropriate.

Each measurement should include a value of uncertainty. In addition, the temperature of the laboratory, and the date of the measurements should be recorded on the certificate.

Any calibrated standards are valuable items and they, their associated certificates, and any records of their measurement should be securely stored; a fireproof safe is recommended.

Measurement practice

Having established the measurement uncertainty, it is considered good laboratory practice to re-measure the standards at specified time intervals; initially this might be every month. It is important that a record of the measurements is kept so that any deviation from the initial measurement, \pm its uncertainty, can be seen. If this is found to happen then the cause must be established. If the laboratory is working within the remit of ISO 9000 then this re-measurement procedure becomes mandatory.

Industry specific standards

It is sometimes more useful to use a standard, or set of standards, that are specific to a particular industry or application within that industry. For example, if a quality control laboratory uses colour measurement to monitor the production of a particular material then it would make sense to establish the uncertainty in the measurements using a master standard of that material. The precision is relatively easy to establish by use of procedure described below, but the accuracy requires that the spectral reflectance of a sample of the material be measured at an ISO/IEC17025 (UKAS) accredited laboratory and the appropriate certificate obtained.

The use of industry specific standards might lead to additional contributions to the measurement uncertainty - for example, fading over time- that must be considered in any associated uncertainty calculations. It is good practice in such cases, to have two nominally identical samples that are considered reference standards; one is used for regular monitoring of the measurement instrument, and the other is kept under controlled conditions, usually in the dark. If a change is noted in the measurements of

the regular sample then the stored sample can be measured. If these results match those of the regular sample then the change must be associated with the instrument; if the change is not seen in the measurement of the stored sample then the change must be associated with the sample.

Fluorescence

It is usual to select samples as reference standards that do not fluoresce. Fluorescence is caused by incident radiation at one wavelength, often in the ultraviolet or blue part of the spectrum, causing the emission of radiation at another, usually higher, wavelength. The fluorescence process is not usually stable over time and thus the spectral properties, and hence the colour of the samples, varies with time.

Fluorescence can also cause a problem if samples are to be measured on two spectrophotometers that have different light sources (for example, tungsten halogen and xenon flash), with different spectral power distributions and / or different ultraviolet cut-off filters (with different spectral absorptions). These differences can lead to different amounts of fluorescent emission, leading to different spectral reflectances being recorded.

4. MEASUREMENT UNCERTAINTY – THEORY

Measurement precision

Precision is a measure of the closeness in agreement between repeated measurements of the same sample under the same conditions: it is also referred to as instrument repeatability. It is defined by the standard deviation, $S(x_i)$, of a series of measurements. If the measurements are repeated n times, the individual readings denoted by x_i , and the mean reading by x_m , then:

$$S(x_i) = \sqrt{\frac{\sum_{i=1}^n (x_i - x_m)^2}{n-1}} \quad (1)$$

It must be recognised that the value of x_m defines the mean of the sample actually measured. This sample is itself a sub-set of the whole population of possible measurements and, if the number of measurements was increased then it is to be expected that the value of the standard deviation, $S(x_i)$, might decrease. The best statistical estimate of the standard deviation of this mean value is given by the standard error, $S(x_m)$:

$$S(x_m) = \frac{S(x_i)}{\sqrt{n}} = \sqrt{\frac{\sum_{i=1}^n (x_i - x_m)^2}{n(n-1)}} \quad (2)$$

Measurement accuracy

The absolute accuracy of a measurement can be equated with the total uncertainty in that measurement and can only be determined by reference to a set of calibrated transfer standards as described above.

Calculation of uncertainty

Uncertainty defines the range of values within which the true value is expected to lie. It is usually quoted at a confidence level of 95%, meaning that there is a 95 % probability that the true value lies within the range of the measured value \pm the total uncertainty.

The total uncertainty is the combination of two uncertainties, those that are the result of random processes and determined statistically, Type A, and those that are systematic, Type B.

The Type A uncertainties, U_A , can be estimated by determining the standard error of the mean of a set of data as described above. Thus:

$$U_A = S(x_m) \quad (3)$$

Practically, Type B uncertainties can be calculated as:

$$U_B = \sqrt{U_N^2 + U_D^2} \quad (4)$$

where U_N is the certified uncertainty of the calibration standard and U_D is the difference between the measured value of the standard and the certified value.

The total uncertainty is then given by:

$$U_T = \sqrt{U_A^2 + U_B^2} \quad (5)$$

Thus, by substitution:

$$U_T = \sqrt{S(x_m)^2 + U_N^2 + U_D^2} \quad (6)$$

Expanded uncertainty

To provide a level of confidence associated with a value of uncertainty, the term expanded uncertainty, U , is used. The total uncertainty is multiplied by a factor k , dependent on the degrees of freedom in the uncertainty determination, to achieve the required confidence level. For most samples this factor will be two, but for dark samples such as blacks and dark blues, where the Type A uncertainty is a significant proportion of the reflectance value it may be higher (See UKAS, 2007 for further details). Typically for a 95% confidence level:

$$U = 2U_T \quad (7)$$

5. MEASUREMENT UNCERTAINTY – PRACTICE

Instrument location

Ensure that the temperature and humidity of the instrument location are stable, within the range stated to be acceptable by the instrument manufacturer, and consistent with normal practical use. It is highly desirable that the same environmental conditions are used as stated on the calibration certificate supplied by the calibration laboratory.

Select a calibrated standard and make sure that it is clean. To obtain the most reproducible results, measurements should be restricted to the central region of the standard. Ideally, a jig should be used to locate the standard centrally over the measurement aperture of the instrument. Alternatively, the back pattern on each standard may be designed to help its location in the same position for each measurement. Matt standards may have a mask of thin paper, with an appropriate size hole in it, placed between the standard and the instrument to help reduce contact of the matt surface with the instrument, prolonging its service life.

As strongly coloured standards might show some thermochromism, they should always be allowed to stabilize at the room temperature before measurement, and care should be taken to avoid undue heating during measurement.

Power up the instrument and allow it to warm up for the length of time recommended by the manufacturer, usually at least 30 mins.

Set the measurement conditions on the instrument to those appertaining to the conditions most frequently used in practice. This refers to the physical settings, for example, specular component of the reflected light included or excluded, UV component included or excluded, aperture size and, for remote measuring, the angle and distance. If the colour measurement procedure usually used in practice involves averaging a series of separate measurements then it must be considered whether this averaging be included in the performance analysis, or eliminated for a more critical analysis.

If appropriate, set the colorimetric conditions in the instrument control software. This refers to the CIE illuminant, CIE observer and CIE colour-difference formula. The following are recommended: D65, 10°, CIE L^* , a^* , b^* . The conditions most frequently used in practice may be substituted.

Characterise the instrument according to the method specified by the manufacturer. This procedure is designed to establish a baseline for reflectance and is often achieved by measuring the instrument response with the lamp switched off.

Note that the order in which the above are performed may be determined by the instrument control software.

Note too that it is sometimes a requirement of the software that a measurement be made of a 'standard' in order that colour differences can be calculated. This is not required for this assessment and so a dummy standard can be used.

Calculation of precision – repeatability

The spectral reflectance of each selected calibrated standard should be measured thirty times with the instrument being re-characterised between each measurement. The thirty sets of measurements are averaged and the values of the standard error, $S(x_m)$, calculated as described above. Note that these calculations are made wavelength by wavelength.

Calculation of accuracy

The difference is found, U_D , between the average values of spectral reflectance calculated above, and those tabulated on the appropriate certificate.

Calculation of uncertainty

Using the values of the standard error, $S(x_m)$, and the reproducibility, U_D , together with the value of measurement uncertainty from the certificate, U_N , the value of the total uncertainty, U_T , together can be calculated. Note that the calibration laboratory does not usually quote the measurement uncertainty for each wavelength measured; a more generic linear equation is given, for example:

$$Uncertainty = a \times Reflectance\% + b$$

or with a break-point:

$$\text{If } R\% \leq x\%, \text{ then } \quad Uncertainty = a \times Reflectance\% + b$$

$$\text{Else if } R\% > x\% \text{ then } \quad Uncertainty = c$$

where $x\%$ is the value of reflectance at which the break-point occurs, a , b and c are constants. The first equation implies that the uncertainty is linearly related to the value of reflectance, and increases as reflectance increases. The second equation implies

linearity up to a specified value of reflectance, and then that the uncertainty has a constant value.

Thus, the uncertainty value associated with each wavelength can be calculated according to the certified reflectance value at that wavelength. Note that the uncertainty value usually quoted is the expanded uncertainty, with a stated covering power (k) appropriate to a 95% confidence level. The certificate uncertainty value must be divided by the covering power (k), typically two, before being used in the equation to calculate the combined uncertainty.

Calculation of expanded uncertainty

The value of expanded uncertainty is calculated by multiplying the total uncertainty by the appropriate coverage factor, typically two, to achieve a 95% confidence level.

Example

30 reflectance measurements	47.23	47.23	47.09
all at one specific wavelength	47.35	47.26	47.09
	47.25	47.51	47.10
	47.27	47.31	47.32
	47.35	47.33	47.08
	47.38	47.27	47.07
	47.29	47.21	47.04
	47.29	47.27	47.17
	47.21	47.21	47.18
	47.26	47.25	47.21
Average reflectance, R_a	47.236 %		
Standard deviation, $S(x_i)$	0.1043		Eqn.1
Standard error, U_A	0.0190		Eqn.2, 3
Certificate reflectance value, R_c	47.27 %		
Difference in reflectance, $R_a - R_c = U_D$	0.0340 %		
Certificate expanded uncertainty, U_N	0.1200 %		
Equivalent uncertainty, $U_N/2$	0.0600 %		
Total uncertainty, U_T	0.0715 %		Eqn.6
Expanded uncertainty, $2U_T$	0.1431 %		Eqn.7

6. COLORIMETRIC UNCERTAINTY

All of the calculations above refer to the calculation of the uncertainty in the measurement of spectral reflectance. What may be of more interest however, is the uncertainty in the colorimetric values, for example L^* , a^* and b^* . There is no recognised standard method to calculate the uncertainty in colorimetric values, although a number of methods are suggested in the bibliography, see Appendix A.

A simple method to obtain an indication of the uncertainty is to calculate the colorimetric values using three reflectance data sets:

- The average of 30 measured datasets for the standard
- The average measured data with the calculated uncertainty added

- The average measured data with the calculated uncertainty subtracted

While only an approximate calculation of colorimetric uncertainty, the values obtained have been found to be very close to those obtained by more rigorous calculations.

Example

The table below gives the spectral reflectance of the glossy green tile, Fig 1, in the CERAM standard CCS Series II set, $R(\lambda)$, from 380 nm to 780 nm in steps of 5 nm, together with values of the associated total uncertainty, U_T .

Wave length	$R(\lambda)$	U_T									
380	5.33	0.09									
385	5.68	0.10									
390	5.96	0.10									
395	6.21	0.11									
400	6.45	0.11	500	27.69	0.30	600	10.85	0.17	700	12.96	0.20
405	6.65	0.11	505	29.32	0.30	605	10.44	0.17	705	13.67	0.21
410	6.86	0.12	510	30.22	0.30	610	10.11	0.16	710	14.38	0.22
415	7.10	0.12	515	30.31	0.30	615	9.83	0.16	715	15.00	0.23
420	7.34	0.12	520	29.63	0.30	620	9.61	0.15	720	15.56	0.24
425	7.62	0.13	525	28.44	0.30	625	9.44	0.15	725	16.00	0.24
430	7.95	0.13	530	26.88	0.30	630	9.32	0.15	730	16.32	0.25
435	8.32	0.14	535	25.18	0.30	635	9.24	0.15	735	16.58	0.25
440	8.79	0.14	540	23.44	0.30	640	9.22	0.15	740	16.71	0.25
445	9.34	0.15	545	21.74	0.30	645	9.24	0.15	745	16.75	0.25
450	10.01	0.16	550	20.14	0.30	650	9.31	0.15	750	16.74	0.25
455	10.80	0.17	555	18.66	0.28	655	9.43	0.15	755	16.71	0.25
460	11.76	0.18	560	17.32	0.26	660	9.59	0.15	760	16.51	0.25
465	12.94	0.20	565	16.11	0.25	665	9.78	0.16	765	16.48	0.25
470	14.37	0.22	570	15.04	0.23	670	10.05	0.16	770	16.24	0.25
475	16.11	0.25	575	14.07	0.22	675	10.38	0.17	775	16.06	0.24
480	18.13	0.27	580	13.24	0.21	680	10.75	0.17	780	15.88	0.24
485	20.46	0.30	585	12.51	0.20	685	11.21	0.18			
490	22.99	0.30	590	11.87	0.19	690	11.75	0.18			
495	25.50	0.30	595	11.32	0.18	695	12.33	0.19			

The table below shows the calculated values of the CIE X , Y , Z , tristimulus values, the CIE chromaticity coordinates, x , y , and the CIELAB coordinates L^* , a^* , b^* , C_{ab}^* , h_{ab} calculated using the CIE Standard Illuminant D65 and the CIE 10° Standard Colorimetric Observer. Also shown are the colorimetric coordinates for the average reflectance, $R(\lambda)$, \pm the associated uncertainty, U_T , and the standard deviation (representing the total uncertainty) of these three values.

	Calculated from $R(\lambda)$	Calculated from $R(\lambda)+U_T$	Calculated from $R(\lambda)-U_T$	Total Uncertainty
X	12.37	12.56	12.18	0.19
Y	18.77	19.01	18.52	0.25

Z	12.72	12.91	12.52	0.19
x	0.2821	0.2823	0.2818	0.0002
y	0.4280	0.4275	0.4284	0.0005
L*	50.41	50.70	50.12	0.29
a*	-13.07	-13.06	-13.08	0.01
b*	40.69	40.70	40.68	0.01
C_{ab}*	-42.74	-42.75	-42.73	0.01
h_{ab}	107.81	107.79	107.82	0.01

These values represent the uncertainty for only one tile, which is located at one place in colour space. If equivalent values are calculated for all 14 of the CERAM tile set (12 colour tiles plus white and black) then the data in the table below are obtained.

	X	Y	Z	x	y	L*	a*	b*	C_{ab}*	h_{ab}
White	0.19	0.25	0.19	0.0002	0.0005	0.29	0.01	0.01	0.01	0.01
Black	0.19	0.25	0.19	0.0002	0.0005	0.29	0.01	0.01	0.01	0.01
Pale Grey	0.28	0.30	0.32	0.0001	0.0001	0.17	0.01	0.01	0.01	0.01
Mid Grey	0.28	0.30	0.32	0.0001	0.0001	0.31	0.01	0.01	0.01	0.01
Difference Grey	0.28	0.30	0.32	0.0001	0.0001	0.31	0.01	0.05	0.05	0.05
Deep Grey	0.08	0.08	0.09	0.0001	0.0000	0.25	0.01	0.01	0.01	0.01
Deep Pink	0.20	0.16	0.16	0.0004	0.0001	0.28	0.01	0.04	0.02	0.04
Red	0.14	0.09	0.04	0.0012	0.0001	0.20	0.01	0.31	0.30	0.31
Orange	0.23	0.22	0.10	0.0007	0.0001	0.18	0.03	0.34	0.34	0.34
Bright Yellow	0.23	0.21	0.05	0.0007	0.0002	0.19	0.04	0.30	0.30	0.30
Green	0.19	0.25	0.19	0.0002	0.0005	0.29	0.01	0.01	0.01	0.01
Difference Green	0.19	0.25	0.18	0.0002	0.0005	0.29	0.01	0.04	0.03	0.04
Cyan	0.18	0.22	0.32	0.0005	0.0005	0.27	0.02	0.18	0.18	0.18
Deep Blue	0.04	0.04	0.11	0.0008	0.0013	0.27	0.04	0.05	0.05	0.05
Maximum values	0.28	0.30	0.32	0.0012	0.0013	0.31	0.04	0.34	0.34	0.12
Rounded values	0.35	0.35	0.35	0.0015	0.0015	0.35	0.05	0.35	0.35	0.15

Note that it is usual to round maximum values up as shown in the table. Also values of 0.00 are replaced by 0.01 because it is unlikely that the uncertainty is exactly equal to zero.

From these data it can be seen that the calculated values of the uncertainty in the colorimetric data varies with the colour of the tile, as might be expected. Thus, it is reasonable to take the maximum value as an indicator of the overall uncertainty of each coordinate, as shown by the rounded data in the bottom line of the table above.¹

7. FURTHER CONTRIBUTIONS TO TYPE B UNCERTAINTY

Wavelength uncertainty

It has been assumed in the above calculations that, when the instrument control software indicates that it is recording data at a specified wavelength, the light being measured can actually be associated with that wavelength. One way of checking this is

¹ Note that the results calculated in the examples above are meant only as an illustration of the method of calculation and must not be taken as representative of the actual calculated values of uncertainty associated with each specific colour tile.

to use a holmium tile that has been calibrated at an accredited laboratory. The spectral reflectance of holmium exhibits a number of sharp peaks that can be associated with specific wavelengths, Fig. 2, and by measuring the tile with an instrument, the location of the peaks can be verified. A difficulty arises in that the accreditation laboratory usually measures the reflectance with a narrow bandwidth, typically 1 nm, in order to adequately resolve the absorption peaks, but this narrow bandwidth is not usually available on typical bench-top and handheld spectrophotometers. Therefore, the judgement of any wavelength error is a somewhat arbitrary process.

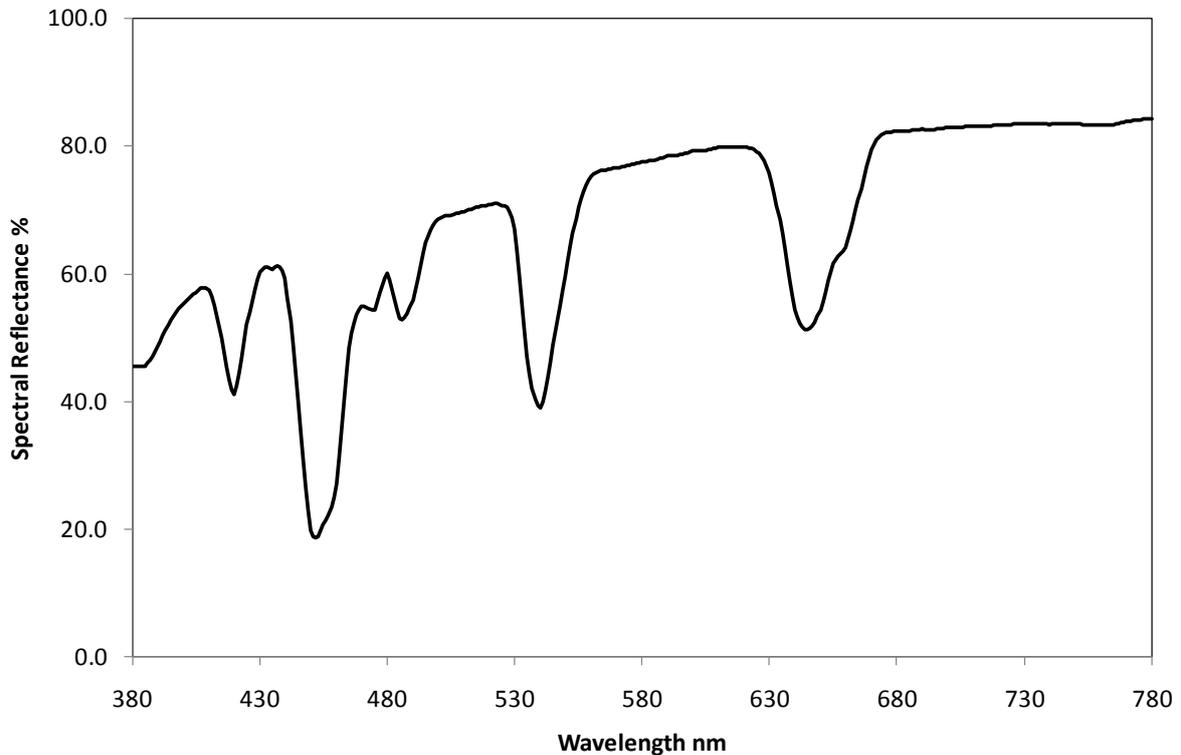


Fig. 2. The spectral reflectance of a holmium tile measured from 380 nm to 780 nm in steps of 1 nm

Temperature variation

Some materials change colour with temperature. This thermochromism occurs with some red, orange, and yellow pigments that contain selenium and it has been shown that, in such cases, it is necessary to standardise the temperature at which the measurements are made. For this purpose, 'room temperature' is often a sufficiently precise definition, because significant changes usually occur only when the sample is quite hot. For purposes of standardisation however, it is more correct that measurements be made at the temperature (and relative humidity) that were used by the calibration laboratory. These values should be found on the calibration certificate supplied by the laboratory.

Although instruments are normally operated at 'room temperature', the samples may warm up under other circumstances. If measurements are made on samples illuminated with 'white' light, then there may be a sufficient rise in sample temperature for some significant thermochromism to take place. This can be checked by taking a series of measurements with the sample left in the measurement position in the instrument; if the measurements show a steady drift with time, thermochromism may be taking place. It can be noted that many modern integrating-sphere based spectrophotometers use a pulsed xenon lamp to provide the illumination, and the very short duration of the flash precludes any significant rise in temperature.

The table below shows the changes in CIELAB values, L^* , a^* , b^* , C_{ab}^* and H_{ab}^* for a 10° C rise in temperature (Δ = value at 25° C minus the value at 35° C); these data are applicable to any geometry and are calculated using CIE Standard Illuminant D65 and the CIE 10° Standard Observer.

	ΔL^*	Δa^*	Δb^*	ΔC_{ab}^*	ΔH_{ab}^*
Pale Grey	+0.03	+0.02	-0.02	-0.03	+0.01
Mid Grey	+0.03	+0.03	-0.04	-0.04	+0.02
Difference Grey	+0.04	-0.04	-0.03	+0.03	+0.05
Deep Grey	+0.00	-0.01	-0.00	+0.00	+0.01
Deep Pink	+0.13	+0.48	+0.23	+0.51	+0.16
Red	+0.55	+0.54	+0.83	+0.93	+0.32
Orange	+0.49	-0.65	+0.67	+0.17	+0.92
Bright Yellow	+0.29	-0.74	-0.03	-0.05	+0.74
Green	+0.20	-0.75	+0.03	+0.68	+0.32
Difference Green	+0.21	-0.79	+0.03	+0.68	+0.38
Cyan	+0.12	-0.34	+0.00	+0.19	-0.29
Deep Blue	+0.00	+0.09	-0.08	+0.12	+0.03

Fading and shelf-life

An industry-selected standard should be tested to see if it changes over time. A way to do this is to have two nominally identical samples and measure both to establish that they are indeed similar. One sample is then kept in the dark and the other in the light. After a specified time they are both re-measured and the results compared. If the measurement of sample kept in the dark is now different from that at time zero then this difference is attributed to a change due to shelf life. If the measurement of sample kept in the dark is now different from that kept in the light then this difference is attributed to a change due to fading. Further measurements must be made to establish the rate of change and then due allowance must be made in the calculation of the total uncertainty.

APPENDIX A:

Bibliography

Alman, D.H. and Billmeyer, F.W., A review of wavelength calibration methods for visible-range photoelectric spectrophotometers, *J. Chem. Educ.*, **52**, A281-A290 (1975).

ASTM E 275, *Practice for Describing Measuring Performance of Ultraviolet, Visible, and Near Infrared Spectrophotometers*, ASTM, West Conshohocken, PA 19428-2959

ASTM E1164, *Standard practice for obtaining spectrometric data for object-color evaluation*, ASTM International, West Conshohocken, PA., U.S.A. (2009).

Berns, R., and Reniff, L., An Abridged Technique to Diagnose Spectrophotometric Errors, *Color Research and Application*, **22**, 51-60 (1997)

Billmeyer, F.W., and Alessi, P.J., Assessment of color-measuring instruments, *Color Res. Appl.*, **6**, 195-202 (1981).

Carter, E.C., and Billmeyer, F.W., Material standards and their use in color measurement, *Color Res. Appl.*, **4**, 96-100 (1979).

CIE Publication 15:2004, *Colorimetry, 3rd ed.*, Commission Internationale de l'Éclairage, Vienna, Austria (2004).

CIE Publication 130:1998: *Practical Methods for the Measurement of Reflectance and Transmittance*, Internationale Commission de l'Eclairage, Vienna, Austria (1998).

CIE Standard 014-2/E:2006/ISO 11664-2:2007(E): Joint ISO/CIE Standard: *CIE Colorimetry — Part 2: Standard Illuminants for Colorimetry*, Internationale Commission de l'Eclairage, Vienna, Austria (2006).

Clarke, F.J.J. and Malkin, F., 1981, *Development of a new series of ceramic colour standards*, *Journal of the Society of Dyers and Colourists*, **97**, 503-504

Clarke, P.J., Hanson, H.R., and Verrill, J.F., Determination of colorimetric uncertainties in the spectrophotometric measurement of colour, *Analytica Chimica Acta*, **380**, 277-284 (1999).

Clarke, P.J., *Surface Colour Measurements*, National Physical Laboratory Good Practice Guide No. 96, National Physical Laboratory, Teddington, England (2006).

Early, E.A., and Nadel, M.E., Uncertainty analysis for reflectance colorimetry, *Color Res. Appl.*, **29**, 205-216 (2004).

Early, E.A., and Nadel, M.E., Uncertainty analysis for reflectance colorimetry, *Color Res. Appl.*, **29**, 205-216 (2004).

Erb, W., and Budde, W., Properties of standard materials for reflection, *Color Res. Appl.*, **4**, 113-118 (1979).

Fairchild, M.D. and Grum, F., 1985, *Thermochromism of ceramic reference tiles* *Applied Optics*, **24**, 3432-3434

Gardner, J.L., *Uncertainties in Surface Colour Measurement*, National Physical Laboratory Good Practice Guide No. 95, National Physical Laboratory, Teddington, England (2006).

Gardner, J.L., Uncertainty estimation in colour measurement, *Color Res. Appl.*, **25**, 349-355 (2000).

Koo, A, Clare, J.F., Nield, K.M., Deadman, A. and Usadi, E., Fluorescence of ceramic color standards, *Appl. Optics*, **49**(12), 2376-2381 (2010).

Malkin, F., Larkin, J.A., Verrill, J.F. and Wardman, R.H., The BCRA - NPL Ceramic Colour Standards, Series II - Master spectral reflectance and thermochromism data, *J. Soc. Dyers and Colourists*, **113**, 84-94 (1997).

UKAS, The Expression of Uncertainty and Confidence in Measurement, 2nd edition (2007).

APPENDIX B

Care of Colour Standards

Gloss and matt standards should be stored in the boxes provided when not in use.

Standards should always be held by the edges to avoid touching the face with fingers as this may leave marks on the surface.

If standards do become marked, they may be cleaned by breathing on the surface and wiping gently with an optical lens tissue.

If this is not sufficient, use a pad of tissue lightly moistened with laboratory grade Propan-2-ol (Isopropyl Alcohol), and dry off.

If this does not work, gently wipe the glaze surface with a pad of tissue moistened with a solution of laboratory grade detergent. The detergent should contain no additives such as bleaching agents, thickeners, colouring agents or fluorescing agents. It should be used following the manufacturers instructions. This is followed by wiping with a pad moistened with clean water and a final wipe dry.

DO NOT subject the standards to running water or immerse them in water.

At all times care shall be taken not to apply undue pressure when cleaning, to avoid a polishing action or the deposition of lint from the tissue on to the surface.

If a standard becomes permanently soiled or damaged, it may be necessary to replace it. This especially applies to matt standards which are very difficult to clean.

Information courtesy of CERAM

APPENDIX C

Calibration Laboratory in UK: National Physical Laboratory:

www.npl.co.uk/optical-radiation-photonics/optical-characterisation-of-materials/products-and-services/ceramic-colour-standards

Calibration Laboratory in UK: CERAM

www.ceram.com/services/colour-standards/

Calibration Laboratory in US: National Institute of Standards and Technology:

www.nist.gov/pml/div685/grp05/color_facility.cfm

Supplier of colour standards: Labsphere

www.labsphere.com

Supplier of colour standards: Avian Technologies

www.avianttechnologies.com