
Analytical colorimetry —
Part 5:
Procedure for colorimetric
determination of colour differences
of object colours according to
equidistant colour spaces

Analyse colorimétrique —

*Partie 5: Mode opératoire pour la détermination colorimétrique
des différences de couleur des couleurs d'objets selon des espaces
colorimétriques équidistants*



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ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Email: copyright@iso.org
Website: www.iso.org

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Contents

	Page
Foreword.....	iv
Introduction.....	v
1 Scope.....	1
2 Normative references.....	1
3 Terms and definitions.....	1
4 Procedure.....	1
5 Test report.....	2
Annex A (informative) OSA-UCS colour space modified by Oleari et al.....	3
Annex B (informative) DIN99o colour space.....	6
Annex C (informative) CAM16-UCS colour space.....	12
Bibliography.....	15

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 256, *Pigments, dyestuffs and extenders*.

A list of all parts in the ISO 18314 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

The scope of ISO/TC 256 is standardization in the field of colorants, i.e. pigments, dyestuffs and extenders. Standards on test metrics in this field is a very effective basis for the introduction and improvement of quality management systems. The consequent use of standardized test metrics within a company can cut down testing costs to a fraction of the original costs. Carefully written test metrics improve the precision of the test results. Standards for pigments, dyestuffs and extenders used as raw materials support the trade of these materials.

Several formulas had been developed in the past for the assessment of colour differences. For presenting colours in a colour space, the CIELAB (CIE 1976 $L^*a^*b^*$) colour space (adopted by ISO and published as ISO/CIE 11664-4)^[1] and colour coordinates are the most prominent. For predicting colour differences, the International Commission on Illumination (CIE) has standardized CIEDE2000 (adopted by ISO and published as ISO/CIE 11664-6)^[2]. The CIEDE2000 formula is intended to be applicable within the sample colour-difference magnitude of 0 to 5 CIELAB units. However, it does not have a new associated analytical colour space, but is still based on CIELAB.

For the steering and adjustment of colorant production or extender production in colorants industry, a uniform colour space (UCS) is an essential tool in addition to a colour difference formula. This requires adjusting colorant formulations in a colour space. Both corrective actions in production and the delivery specifications with customers are based on tolerance ellipsoids in the colour space applied. In CIE 217, different colour difference formulas and colour space models have been analysed using actual and reliable visual data sets. Several models gave similar performance, so no specific uniform colour space model or Euclidian colour-difference formula can be proposed performing statistically significantly better than CIEDE2000. However, three colour spaces stood out: OSA-UCS, DIN99o and CAM02-UCS, in chronological order of their publications. In this document, the actual editions of these models are standardized for the assessment of coloristic properties of pigments, dyestuff and extenders.

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Analytical colorimetry —

Part 5:

Procedure for colorimetric determination of colour differences of object colours according to equidistant colour spaces

1 Scope

This document specifies the procedure and test report for determining small colour differences of object colours according to equidistant colour spaces. Three suggestions for metrics for the quantitative determination of small colour differences ($\Delta E < 5$) of non-luminous colours are given in [Annexes A, B and C](#). These examples are related to the three colour space models: OSA-UCS modified by Oleari et al., DIN99o and CAM16-UCS (uniform colour space).

This document is applicable for the assessment of pigments, dyestuff and extenders in the field of coatings, plastic and prints only that are evaluated in pairs for colour conformity, and which have small perceptible colour differences.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

4 Procedure

For determining small colour differences ($\Delta E < 5$) of object colours according to equidistant colour spaces, one of the three procedures from [Annexes A, B and C](#) should be used. Three suggestions for metrics for the quantitative determination of small colour differences of non-luminous colours are given in detail in [Annexes A, B and C](#) for information. These examples are related to the three colour space models OSA-UCS modified by Oleari et al., DIN99o¹⁾ and CAM16-UCS. Further information on these models can be found in References [\[11\]](#) to [\[31\]](#).

The used calculation metric for the colour difference shall be stated in the test report.

When the formulae described in [Annexes A, B and C](#) are used for large colour differences (greater than approximately 10 CIELAB units), larger deviations between calculated colour differences and visual evaluations are to be expected. This is due to a nonlinear relationship between small and large colour differences. If it is intended to use the formulae in this range, it should be explicitly agreed between the interested parties.

1) DIN99o was denoted DIN99b^[19] but has later been referred to as DIN99o ^[18] ^[21].

5 Test report

The test report shall contain at least the following information:

- a) all details necessary to identify the product tested;
- b) a reference to this document, i.e. ISO 18314-5:2022;
- c) the colour space model used for the determination of the colour differences;
- d) the results of the test;
- e) any deviations from the procedure specified;
- f) any unusual features (anomalies) observed during the test;
- g) the date of the test.

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Annex A (informative)

OSA-UCS colour space modified by Oleari et al.

A.1 Description of the modified OSA-UCS colour space

The OSA-UCS colour space was first published in 1947 by the Optical Society of America (OSA) and further developed in the subsequent years. The model is based on the characterization of colours using approximately 500 lattice points in a regular rhombohedral shape in an Euclidian space. This can be illustrated by a cube with each of the eight corners being cut symmetrically. The CIE 10° standard observer and the D65 standard illuminant was used. This colour space is based on the three perpendicular coordinates lightness: L_{OSA} , Jaune J (the yellow/blue axis) and Green G (the green/red axis).

For OSA-UCS lightness, L_{OSA} , the value of 0 corresponds to a 30 % reflective neutral background. Assuming nearly zero values for G , positive values of J indicate yellowish or brownish colours, and negative values of J blue colours.

Assuming nearly zero values for J , positive values of G indicate greens and negative values of G purple colours.

In this document, Oleari's concept of a logarithmic compression in chroma and lightness leading to ΔE_E is applied, using the new coordinates J , and G . Further details are described in [A.2](#) and the References [\[12\]](#) to [\[17\]](#).

For the transformation from the X_{10} , Y_{10} , Z_{10} coordinates or the x_{10} , y_{10} , z_{10} -chromaticity coordinates, respectively to the OSA-UCS system proposed by Oleari, the following and [Formulae \(A.1\) to \(A.5\)](#) are applied:

Let (Y_{10}, x_{10}, y_{10}) and (L_{OSA}, J, G) be the colour specification in two spaces. The unit of distance in the OSA-UCS space is approximately 10 just noticeable difference, assuming that this space conforms to Euclidean metrics.

The lightness is defined as in the original OSA-UCS formula [\[Formula \(A.1\)\]](#):

$$L_{OSA} = \left\{ 5,9 \left[\left(Y_0^{1/3} - \frac{2}{3} \right) + 0,042(Y_0 - 30)^{1/3} \right] - 14,4 \right\} \frac{1}{\sqrt{2}} \quad (A.1)$$

with

$$Y_0 = Y_{10} \left(4,493 \ 4x_{10}^2 + 4,303 \ 4y_{10}^2 - 4,276 \ 0x_{10}y_{10} - 1,374 \ 4x_{10} - 2,564 \ 3y_{10} + 1,810 \ 3 \right).$$

The lightness L_{OSA} has no simple analytical conversion from the OSA-UCS space to the tristimulus space.

The coordinates J and G , which correspond to the empirical j and g of the OSA-UCS system, are obtained by a sequence of linear transformations and a logarithmic compression – see [Formula \(A.2\)](#) and [Formula \(A.3\)](#):

$$\begin{pmatrix} A \\ B \\ C \end{pmatrix} = \begin{bmatrix} 0,659 \ 7 & 0,449 \ 2 & -0,108 \ 9 \\ -0,305 \ 3 & 1,212 \ 6 & 0,092 \ 7 \\ -0,037 \ 4 & 0,479 \ 5 & 0,557 \ 9 \end{bmatrix} \begin{pmatrix} X_{10} \\ Y_{10} \\ Z_{10} \end{pmatrix}, \quad (A.2)$$

$$\begin{pmatrix} J \\ G \end{pmatrix} = \begin{bmatrix} S_J & 0 \\ 0 & S_G \end{bmatrix} \begin{bmatrix} -\sin \alpha & \cos \alpha \\ \sin \beta & -\cos \beta \end{bmatrix} \begin{pmatrix} \ln \left(\frac{A/B}{A_n/B_n} \right) \\ \ln \left(\frac{B/C}{B_n/C_n} \right) \end{pmatrix}$$

$$= \begin{bmatrix} 2(0,573 \ 5L_{OSA} + 7,089 \ 2) & 0 \\ 0 & -2(0,764 \ 0L_{OSA} + 9,252 \ 1) \end{bmatrix} \begin{bmatrix} 0,179 \ 2 & 0,983 \ 7 \\ 0,948 \ 2 & -0,317 \ 5 \end{bmatrix} \begin{pmatrix} \ln \left(\frac{A/B}{0,936 \ 6} \right) \\ \ln \left(\frac{B/C}{0,980 \ 7} \right) \end{pmatrix} \quad (A.3)$$

S_G and S_J are suitable normalization-scale factors and α and β are the angles between the reference axes of the main chromatic opponent functions and the directions of parallel lines with constants g and j , respectively^[11]. A_n , B_n and C_n are the values of A , B and C according to [Formula \(A.3\)](#) for the neutral standard illuminant D65.

The analytical reversibility of this transformation is straightforward, excluding the conversion of L_{OSA} .

The chroma and hue angles are obtained in OSA-UCS space from J and G coordinates as in CIELAB from a^* and b^* according to [Formulae \(A.4\)](#) and [\(A.5\)](#):

$$C_{OSA} = \sqrt{J^2 + G^2} \quad (A.4)$$

$$h_{OSA} = \arctan \left(\frac{J}{-G} \right) \quad (A.5)$$

NOTE h_{OSA} is expressed in degrees (°).

A.2 Determination of colour differences according to OSA-UCS colour space modified by Oleari et al.

From colour space proposed by Oleari et al. (see [A.1](#)), the colour-difference formula ΔE_{GP} ^[12] was introduced. Next, based on a logarithmic compression of the OSA-UCS coordinates in the colour space modified by Oleari et al., new coordinates L_E , J_E , G_E were proposed, defining a new colour space with an Euclidean colour-difference formula named ΔE_E ^[13]. The ΔE_{GP} and ΔE_E colour-difference formulas were tested by CIE/TC 1-55 in CIE 217, together with CIEDE2000, DIN99o and other colour-difference formulas.

Based on the original coordinates OSA-chroma C_{OSA} and L_{OSA} , the definitions of this formula and of the OSA-UCS space with chroma and lightness log compressed are recalled by [Formula \(A.6\)](#) to [Formula \(A.10\)](#):

$$\Delta E_E = \sqrt{(\Delta L_E)^2 + (\Delta G_E)^2 + (\Delta J_E)^2}, \quad (A.6)$$

$$L_E = \left(\frac{1}{b_L} \right) \ln \left[1 + \frac{b_L}{a_L} (10L_{OSA}) \right] \quad (A.7)$$

with $a_L = 2,890$, $b_L = 0,015$,

$$G_E = -C_E \cos(h),$$

$$J_E = C_E \sin(h), \quad (A.8)$$

with

$$h = \arctan\left(-\frac{J}{G}\right),$$

$$C_E = \left(\frac{1}{b_c}\right) \ln \left[1 + \frac{b_c}{a_c} (10C_{OSA}) \right] \quad (A.9)$$

with $a_c = 1,256$, $b_c = 0,050$,

$$C_{OSA} = \sqrt{G^2 + J^2} . \quad (A.10)$$

Greater insight into this concept and the introduction or derivation of the colour coordinates, as well as the formulae, can be obtained from References [14] to [17].

Annex B (informative)

DIN99o colour space

B.1 Description of the DIN99o colour space

B.1.1 General

The DIN99o formula was the result of the adjustment of the parameters of the well-established CIELAB colour space. The goal was to fit the results of the colour differences according to CIEDE2000 but keeping the properties of a colour space. Vectors are no longer of significance in the CIEDE2000 formula, therefore, there is no colour space based on the CIEDE2000 formula.

B.1.2 Determination of coordinates L_{99o} , a_{99o} , b_{99o} , C_{99o} , h_{99o} of the DIN99o formula

The starting point for the determination of the colour coordinates L_{99o} , a_{99o} , b_{99o} , C_{99o} , h_{99o} of the DIN99o formula is the determination of the colour coordinates L^* , a^* , b^* according to ISO/CIE 11664-4. The colour coordinates L_{99o} , a_{99o} , b_{99o} , C_{99o} , h_{99o} are determined according to [Formulae \(B.1\)](#) to [Formula \(B.15\)](#) [for calculation examples see [B.2](#)]:

$$\text{DIN 99o lightness:} \quad L_{99o} = 303,67 \ln (1,0 + 0,0039 L^*)/k_E \quad (\text{B.1})$$

$$\text{Auxiliary variable for redness:} \quad e_o = a^* \cos 26^\circ + b^* \sin 26^\circ \quad (\text{B.2})$$

$$\text{Auxiliary variable for yellowness:} \quad f_o = -0,83 a^* \sin 26^\circ + 0,83 b^* \cos 26^\circ \quad (\text{B.3})$$

$$\text{Auxiliary variable for chroma:} \quad G_o = (e_o^2 + f_o^2)^{0,5} \quad (\text{B.4})$$

$$\text{Auxiliary variable for hue angle:} \quad h_{\text{eoffo}} = \arctan (f_o/e_o) \quad \text{for } e_o > 0 \text{ and } f_o \geq 0 \quad (\text{B.5})$$

$$(\text{in radians}) \quad h_{\text{eoffo}} = \pi/2 \quad \text{for } e_o = 0 \text{ and } f_o > 0 \quad (\text{B.6})$$

$$h_{\text{eoffo}} = \pi + \arctan (f_o/e_o) \quad \text{for } e_o < 0 \quad (\text{B.7})$$

$$h_{\text{eoffo}} = 3\pi/2 \quad \text{for } e_o = 0 \text{ and } f_o < 0 \quad (\text{B.8})$$

$$h_{\text{eoffo}} = 2\pi + \arctan (f_o/e_o) \quad \text{for } e_o > 0 \text{ and } f_o < 0 \quad (\text{B.9})$$

$$h_{\text{eoffo}} = 0 \quad \text{for } e_o = 0 \text{ and } f_o = 0 \quad (\text{B.10})$$

DIN 99o variable:

DIN 99o hue angle
in degrees:

$$h_{99o} = (h_{\text{e}ofo} 180^\circ/\pi) + 26^\circ \quad \text{for } h_{\text{e}ofo} < 334^\circ \pi/180^\circ \quad (\text{B.11})$$

$$h_{99o} = [(h_{\text{e}ofo} - 2\pi)180^\circ/\pi] + 26^\circ \quad \text{for } h_{\text{e}ofo} \geq 334^\circ \pi/180^\circ \quad (\text{B.12})$$

DIN 99o chroma: $C_{99o} = [\ln(1 + 0,075 G_o)] / (0,043 5 k_{\text{CH}} k_E)$ (B.13)

DIN 99o green-redness: $a_{99o} = C_{99o} \cos(h_{99o} \pi/180^\circ)$ (B.14)

DIN 99o blue-yellowness: $b_{99o} = C_{99o} \sin(h_{99o} \pi/180^\circ)$ (B.15)

Parameters k_{CH} and k_E : See [B.2.3](#)

B.1.3 Determination of the colour coordinates L^* , a^* , b^* , C^* , h according to ISO/CIE 11664-4 from given colour coordinates L_{99o} , a_{99o} , b_{99o} , C_{99o} and h_{99o}

If colour coordinates L_{99o} , a_{99o} , b_{99o} , or L_{99o} , C_{99o} , h_{99o} are given, the colour coordinates L^* , a^* , b^* , C^* and h can be calculated according to ISO/CIE 11664-4. See [Formula \(B.16\)](#) to [Formula \(B.30\)](#):

DIN 99o chroma: $C_{99o} = [(a_{99o})^2 + (b_{99o})^2]^{0,5}$ (B.16)

DIN 99o hue angle: $h_{99o} = 180^\circ \arctan(b_{99o}/a_{99o})/\pi$ for $a_{99o} > 0$ and $b_{99o} \geq 0$ (B.17)

(in degrees) $h_{99o} = 90^\circ$ for $a_{99o} = 0$ and $b_{99o} > 0$ (B.18)

$$h_{99o} = 180^\circ + 180^\circ \arctan(b_{99o}/a_{99o})/\pi \quad \text{for } a_{99o} < 0 \quad (\text{B.19})$$

$$h_{99o} = 270^\circ \quad \text{for } a_{99o} = 0 \text{ and } b_{99o} < 0 \quad (\text{B.20})$$

$$h_{99o} = 360^\circ + 180^\circ \arctan(b_{99o}/a_{99o})/\pi \quad \text{for } a_{99o} > 0 \text{ and } b_{99o} < 0 \quad (\text{B.21})$$

$$h_{99o} = 0 \quad \text{for } a_{99o} = 0 \text{ and } b_{99o} = 0 \quad (\text{B.22})$$

Auxiliary variable
in radians:

$$h_{\text{e}ofo} = (h_{99o} - 26^\circ) \pi/180^\circ \quad (\text{B.23})$$

Auxiliary variable for
chroma:

$$G_o = [\exp(0,043 5 C_{99o} k_{\text{CH}} k_E) - 1,0] / 0,075 \quad (\text{B.24})$$

Auxiliary variable for
green-redness:

$$e_o = G_o \cos(h_{\text{e}ofo}) \quad (\text{B.25})$$

Auxiliary variable for
blue-yellowness:

$$f_o = G_o \sin(h_{\text{e}ofo}) \quad (\text{B.26})$$

CIELAB green-red-ness: $a^* = e_o \cos 26^\circ - (f_o/0,83) \sin 26^\circ$ (B.27)

CIELAB blue-yellow-ness: $b^* = e_o \sin 26^\circ + (f_o/0,83) \cos 26^\circ$ (B.28)

CIELAB chroma: $C^* = [(a^*)^2 + (b^*)^2]^{0,5}$ (B.29)

CIELAB lightness: $L^* = [\exp (L_{990} k_E/303,67) - 1]/0,003 \ 9$ (B.30)

If C_{990} and h_{990} are given, first calculate the auxiliary variable h_{eof_0} in radians [see [Formula \(B.23\)](#)]. Then carry out the calculation steps as described above, beginning with [Formula \(B.24\)](#).

The colour differences can be calculated from the respective values shown in more detail in [Annex B](#). For this purpose, the above calculation is carried out for both the reference and the specimen.

B.2 Determination of colour differences according to DIN99o colour space

B.2.1 Determination of colour differences according to DIN99o formula

The colour difference ΔE_{990} is calculated according to the DIN99o formula as in [Formula \(B.31\)](#):

DIN 99o colour difference: $\Delta E_{990} = [(\Delta L_{990})^2 + (\Delta a_{990})^2 + (\Delta b_{990})^2]^{0,5}$ (B.31)

Parameter k_E : See [Clause B.2.3](#).

If the indices P (specimen) and B (reference) are used for the colours to be compared, [Formula \(B.32\)](#) to [Formula \(B.34\)](#) should be applied.

DIN 99o lightness difference: $\Delta L_{990} = L_{990,P} - L_{990,B}$ (B.32)

DIN 99o red-green difference: $\Delta a_{990} = a_{990,P} - a_{990,B}$ (B.33)

DIN 99o yellow-blue difference: $\Delta b_{990} = b_{990,P} - b_{990,B}$ (B.34)

B.2.2 Separation into lightness, chroma and hue differences

Analogous to the separation of the colour difference into lightness, chroma and hue differences in accordance with ISO/CIE 11664-4, the following applies for the DIN99o formula in the event that $C_{990,P} > 0$ and $C_{990,B} > 0$:

DIN 99o colour difference according to [Formula \(B.35\)](#).

$$\Delta E_{990} = [(\Delta L_{990})^2 + (\Delta C_{990})^2 + (\Delta H_{990})^2]^{0,5} \quad (\text{B.35})$$

Using the indices defined in [B.2.1](#), the following applies:

DIN 99o chroma difference according to with [Formula \(B.36\)](#):

$$\Delta C_{99o} = C_{99o,P} - C_{99o,B} \quad (\text{B.36})$$

DIN 99o hue difference according to [Formula \(B.37\)](#):

$$\begin{aligned} \Delta H_{99o} &= -(a_{99o,P} b_{99o,B} - a_{99o,B} b_{99o,P}) / [0,5 (C_{99o,P} C_{99o,B} + a_{99o,P} a_{99o,B} + b_{99o,P} b_{99o,B})]^{0,5} \\ &= [2(C_{99o,P} C_{99o,B} - a_{99o,P} a_{99o,B} - b_{99o,P} b_{99o,B})]^{0,5} \end{aligned} \quad (\text{B.37})$$

B.2.3 The k factors

The magnitude of perceived colour differences between two colour specimens not only depends on colour differences as determined by colorimetry but is also influenced to varying degrees by surrounding viewing conditions. The k factors are suitable to describe this influence. The two k factors have different meanings: k_{CH} is a form factor describing a relative shifting of weightings in the ratio of the lightness difference to the difference of chroma and hue, k_E describes the influence that changes in viewing conditions have on the total colour difference. Normally, k_E should therefore be equal to 1. Changes in viewing conditions or materials (e.g. textiles) can be considered by the appropriate selection of k_E and k_{CH} values. Values of k_E and k_{CH} other than 1 lead to a change in both colour differences and colour coordinates. If it is intended to use k factors other than 1, their values shall be agreed upon and indicated in the measurement report.

NOTE The k factors have been simplified here compared with CIE 101. For the k factors k_C and k_H , the same weightings are assumed, so that they can be combined to form a k factor k_{CH} . Furthermore, the influence on the total colour difference is always described here by factor k_E and no longer in part by the weightings of all individual differences. By doing so, the k factor for the lightness difference no longer needs to be defined, and the factor merely functions as a form factor. The previously established designations of weightings change as a result.

If it is intended to verify the measured colour differences visually, the following reference conditions shall be met in accordance with [Formula \(B.38\)](#):

$$k_E = k_{CH} = 1 \quad (\text{B.38})$$

In correspondence with CIE 101 and CIE 116, the reference conditions are defined as follows:

Illuminating light source:	D65 simulator
Illuminance:	1 000 lx
Observer:	normal colour vision
Surrounding field:	consistently medium-grey, $L^* = 50$
Size of the specimen:	larger than 4° field of view
Separation of the specimens:	direct contact
Surface texture:	homogeneous
Type of appearance:	object colour
Lightness of specimens:	medium, about $L^* = 50$
Magnitude of colour difference:	less than 5 CIELAB units

If deviating from these reference conditions, a change in the perceived size of a colour difference of a given pair of specimens is to be expected. To describe this change, it is permitted to give the k factors appropriate values other than 1.

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B.2.4 Calculation examples

Table B.1 shows examples of transformations for reference illuminant D65 for the DIN99o model.

Table B.1 — Examples of transformations for reference illuminant D65

L^*	a^*	b^*	L_{99o}	a_{99o}	b_{99o}	c_{99o}	h_{99o}
50,000	10,000	10,000	54,098	12,215	10,979	16,424	41,950
50,000	50,000	50,000	54,098	31,237	28,076	42,000	41,950
50,000	-10,000	10,000	54,098	-11,067	9,780	14,769	138,531
50,000	-50,000	50,000	54,098	-29,384	25,968	39,214	138,531
50,000	-10,000	-10,000	54,098	-12,215	-10,979	16,424	221,950
50,000	-50,000	-50,000	54,098	-31,237	-28,076	42,000	221,950
50,000	10,000	-10,000	54,098	11,067	-9,780	14,769	318,531
50,000	50,000	-50,000	54,098	29,384	-25,968	39,214	318,531
0,000	0,000	0,000	0,000	0,000	0,000	0,000	–
100,000	0,000	0,000	100,000	0,000	0,000	0,000	–

Greater insight into this concept and the formulae can be obtained from References [18] to [22].

Annex C (informative)

CAM16-UCS colour space

C.1 Description of the CAM16-UCS colour space

Colour appearance models are mainly used to predict colour appearance under different viewing conditions such as illuminant, luminance, background, surround conditions. It has been widely used in imaging and illumination. CIECAM02 (CIE 159) was proposed by CIE for colour management for imaging applications. It has been widely used for cross-media colour reproduction, e.g. between reflective printed and self-luminous display colours.

The CIECAM02 model has the following steps:

- a) the input CIE 1931 tristimulus values, X , Y , Z , are converted into illuminant colour adaptation signals via a linear chromatic adaptation transform, referred to as CAT02;
- b) the model maps the illuminant colour adaptation signals into cone-like responses using the Hunt-Pointer-Estévez (HPE) matrix^{[23],[24]}.
- c) the model applies a nonlinear post-adaptation response compression function to the cone-like responses;
- d) the model predicts the perceptual attribute correlates from the post-adaptation cone-like signals.

CIECAM02 was extended to predict colour difference for the surface colours. It was named CAM02-UCS and was documented by CIE in 2018 (CIE 015). Furthermore, illumination researchers did comprehensive investigations and identified advantages to including CAM02-UCS in colour rendering metrics for the lighting industry. These advantages include giving accurate uniform colour spacing in predicting colour difference, robust chromatic adaptation in estimating chromaticity between different illuminants and reliable colour appearance effects under different illuminations. This resulted in the CIE recommending a colour fidelity index, R_f (CIE 224). In addition, Reference [10] derived additional metrics that convey more information than any previous attempt at characterizing colour rendering of light sources.

In 2016, it was found that computational failures can occur in certain cases such as during the image processing of cross-media colour reproduction applications^[26]. Therefore, CIECAM02 was revised to become CAM16. Its uniform colour space CAM02-UCS and chromatic adaptation CAT02 were also revised to become CAM16-UCS and CAT16 respectively. It is expected that they will become CIECAM16 and CIECAT02 in 2022. In this document, only the uniform colour space is given here.

Starting from the X , Y and Z , or X_{10} , Y_{10} , Z_{10} , together with four parameters to define viewing condition, the CAM16 model defines the lightness J , chroma C , hue composition H , hue angle h , colourfulness M , saturation s , and brightness Q . The four parameters to define viewing condition are illuminant (X_w , Y_w and Z_w), adapting luminance (L_a), luminance factor of the background (Y_b), surround (average, dim and dark). The corresponding colour space CAM16-UCS is based on the properties J' for lightness, M' for colourfulness and h for the hue angle. When computing colour differences, the 1964 coordinates X , Y and Z are frequently used.

Ten pairs of samples for the application in the coating industry were calculated and the results are listed in [Table C.1](#). The parameters used were X_{10} , Y_{10} , Z_{10} of [97,29, 100,0, 116,15] under D65/10 condition, Y_b of 20,0, L_a = of 60 cd/m² for a luminance of 300 cd/m² of the reference white, and 'average' surround. The output CAM16-UCS values were calculated from [Formulae \(C.1\) to \(C.3\)](#).

Table C.1 — Examples for CAM16 calculations

No.	X	Y	Z	J'	M'	h	a'	b'	ΔE
1	18,691 1	19,701 8	20,846 3	54,25	3,96	134,55	-2,78	2,82	2,88
	16,298 5	17,192 5	18,225 1	51,15	3,86	136,19	-2,79	2,67	
2	57,455 9	60,603 8	64,452 9	84,34	5,28	137,51	-3,90	3,57	3,39
	50,208 8	52,931 8	56,173 6	80,33	5,08	135,97	-3,65	3,53	
3	8,945 5	9,441 9	9,829 8	39,08	3,54	130,07	-2,28	2,71	3,24
	7,226	7,619 9	7,942 6	35,35	3,27	129,41	-2,08	2,53	
4	14,04	9,95	5,028 7	41,47	27,14	27,35	24,11	12,47	3,83
	15,325 2	10,005 6	4,126 8	41,89	31,97	26,14	28,70	14,08	
5	18,902 8	18,591 4	31,568 4	53,10	15,00	275,90	1,54	-14,92	2,97
	18,522 3	18,675 8	32,576 5	53,09	16,07	264,51	-1,54	-16,00	
6	16,370 3	19,007 8	30,367 5	52,93	18,83	220,43	-14,33	-12,21	2,81
	16,968 8	19,093 5	31,979 9	53,14	18,56	229,53	-12,05	-14,12	
7	6,155 5	6,461 5	19,493 8	32,36	25,13	248,45	-9,23	-23,38	3,46
	6,727 9	6,503 2	21,444 2	32,67	25,78	257,70	-5,49	-25,19	
8	6,292 1	6,215 6	19,512	31,93	24,84	255,85	-6,07	-24,08	2,98
	6,074 3	6,256 3	20,793 3	31,85	26,55	249,60	-9,26	-24,89	
9	17,331 2	18,584 2	18,974 9	52,84	5,75	138,37	-4,30	3,82	2,49
	17,410 3	18,668 6	17,353 8	52,95	7,15	120,12	-3,59	6,18	
10	17,400 2	18,584 2	21,160 9	52,84	5,21	179,12	-5,21	0,08	2,51
	17,057 2	18,668 6	21,255 1	52,85	7,70	180,01	-7,70	0,00	

The colour differences can be calculated from the respective values and are described and in more detail in [C.2](#).

C.2 Determination of colour differences according to CAM16-UCS colour space

Starting from the CIE 1931-coordinates X , Y and Z (under a test illuminant X_w , Y_w and Z_w) the CAM16 model defines the lightness J , chroma C , hue composition H , hue angle h , colourfulness M , saturation s , and brightness Q . The corresponding colour space CAM16-UCS is based on the properties J for lightness, M for colourfulness and h for the hue angle.

The CAM16-UCS has been derived by Li et al.^[26], based on the orthogonal appearance correlates J' , M' and h' that represent be lightness, colourfulness and hue angle, respectively. They are computed using the CIECAM16 model. The uniform colour space based on CAM16 is given by [Formula \(C.1\)](#) to [Formula \(C.5\)](#):

$$J' = \frac{17 J}{1 + 0,007 J} \quad (\text{C.1})$$

$$M' = \ln(1 + 0,022 8 M) / 0,022 8 \quad (\text{C.2})$$

$$a' = M' \cos(h) \quad (\text{C.3})$$

$$b' = M' \sin(h) \quad (\text{C.4})$$