



ISBN 3 901 906 42 8

COMMISSION INTERNATIONALE DE L'ECLAIRAGE
INTERNATIONAL COMMISSION ON ILLUMINATION
INTERNATIONALE BELEUCHTUNGSKOMMISSION

TECHNICAL REPORT

CRITERIA FOR THE EVALUATION OF EXTENDED-GAMUT COLOUR ENCODINGS

CIE 168:2005

UDC: 535.64

Descriptor: Colour systems, colour theories

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Tagungen werden alle vier Jahre abgehalten, in der die Arbeiten der Divisionen überprüft und berichtet und neue Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als höchste Autorität für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterhält sie eine bedeutende Stellung unter den internationalen Organisationen.

Published by the

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This Technical Report has been prepared by CIE Technical Committee 8-05 of Division 8 "Image Technology" and has been approved by the Board of Administration of the Commission Internationale de l'Eclairage for study and application. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory. The latest CIE proceedings or CIE NEWS should be consulted regarding possible subsequent amendments.

Ce rapport technique a été élaboré par le Comité Technique CIE 8-05 de la Division 8 "Technologie des images" et a été approuvé par le Bureau de la Commission Internationale de l'Eclairage, pour étude et emploi. Le document expose les connaissances et l'expérience actuelles dans le domaine particulier de la lumière et de l'éclairage décrit ici. Il est destiné à être utilisé par les membres de la CIE et par tout les intéressés. Il faut cependant noter que ce document est indicatif et non obligatoire. Il faut consulter les plus récents comptes rendus de la CIE, ou le CIE NEWS, en ce qui concerne des amendements nouveaux éventuels.

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CRITERIA FOR THE EVALUATION OF EXTENDED-GAMUT COLOUR ENCODINGS

SUMMARY

The CIE TC 8-05 terms of reference include defining a "minimal set of standard colour spaces that addresses a wide range of imaging applications". One set of applications that was identified by the committee required the use of extended-gamut colour encodings. This document defines a set of objective metrics for evaluating the characteristics of output-referred extended-gamut colour encodings. Detailed metrics have been developed to evaluate a number of important attributes of extended-gamut colour encodings. These criteria include:

- gamut volume characteristics,
- colour quantization characteristics,
- hue constancy when applying non-linear tone scale modifications to RGB colour values,
- complexity of transformation required to and from typical standard spaces (sRGB, ICC PCS, etc.).

The relative importance of the individual metrics will vary on an application-by-application basis. As a result, the committee concluded that the actual evaluation of candidate colour encodings for use in particular applications should be left to other standards bodies that are more closely aligned with the relevant industry segments, and therefore would be better able to define the appropriate application-dependent requirements.

Note that Matlab scripts and data sets used to calculate many of the metrics described in this report can be downloaded from: <http://www.colour.org/tc8-05/documents.html> (see item entitled "CIE TC8-05 Color Encoding Criteria Matlab Scripts"). This information will also be archived at CIE Central Bureau.

CRITERES D'EVALUATION DES ENCODAGES COULEUR A GAMME ETENDUE

RESUME

Un domaine d'activité du comité TC 8-05 concerne la définition d'un ensemble minimal d'espaces couleur standards applicable à une grande variété d'applications d'imagerie. Un ensemble d'applications qui fut identifié par le comité nécessitait l'emploi d'encodages couleur à gamme étendue. Ce document définit un ensemble de mesures objectives de performances pour évaluer les caractéristiques des encodages couleur à gamme étendue référés à la sortie. Des mesures d'évaluation détaillées ont été développées pour des attributs importants des encodages couleur à gamme étendue. Ces critères comprennent:

- les caractéristiques du volume de la gamme,
- les caractéristiques de la quantification couleur,
- la constance des tonalités chromatiques lorsqu'on applique des modifications non linéaires d'échelle de nuances aux composantes RVB,
- la complexité des transformations de passage à, ou en provenance de, un espace standard typique (sRGB, ICC, PCS etc.).

L'importance relative de telle ou telle métrique varie d'une application à l'autre. En conséquence, le comité a conclu que l'évaluation définitive d'encodages couleur candidats en vue d'applications particulières devrait être laissée à d'autres organismes de normalisation plus près des segments industriels visés, et donc plus à même de définir les exigences appropriées aux applications.

Notez que des scripts Matlab ainsi que des fichiers-données utiles aux calculs de plusieurs des mesures de performances décrites dans ce rapport peuvent être téléchargées du site <http://www.colour.org/tc8-05/documents.html> (voir la rubrique "CIE TC8-05 Color Encoding Criteria Matlab Scripts"). Cette information sera également archivée au Bureau Central de la CIE.

MERKMALE ZUR BEWERTUNG VON FARBRÄUMEN MIT VERGRÖSSERTEM FARBUMFANG

ZUSAMMENFASSUNG

Der Arbeitsbereich von CIE TC 8-05 umfaßt auch die Bestimmung einer kleinstmöglichen Serie von Farbräumen, die ein breites Feld von Bildverarbeitungsanwendungen anspricht. Das Komitee hat eine Reihe von Anwendungen identifiziert, die Farbräume mit vergrößertem Farbumfang erfordern. In diesem Dokument werden Berechnungsverfahren zur Bewertung von Wiedergabefarbräumen mit vergrößertem Farbumfang definiert. Detaillierte Methoden zur Ermittlung einer Reihe wichtiger Merkmale von Farbräumen mit vergrößertem Farbumfang sind entwickelt worden. Diese umfassen:

- Kenndaten des Farbumfangs
- Eigenschaften der Farbquantisierung
- Richtlinien zur Erhaltung des Farbtons bei Anwendung nichtlinearer Modifikationen auf RGB Werte
- Aufwandsabschätzungen für die Transformationen in und von standardisierten Farbräumen (sRGB, ICC, PCS, usw.).

Die relative Wichtigkeit der einzelnen Merkmale hängt von der Anwendung ab. Daher kam das Komitee zu dem Schluss, die tatsächliche Ermittlung möglicher Farbräume für bestimmte Anwendungen anderen Normungsorganisationen zu überlassen, die mit den entsprechenden Industriezweigen in näherer Verbindung stehen und daher besser in der Lage sind, die geeigneten anwendungsabhängigen Anforderungen zu definieren.

Die Programmpakete in Matlab und die Datensätze zur Berechnung nach den in diesem Bericht angegebenen Verfahren können von folgender Adresse herunter geladen werden: <http://www.colour.org/tc8-05/documents.html> (siehe Punkt "CIE TC8-05 Color Encoding Criteria Matlab Scripts"). Diese Informationen werden auch im Zentralbüro der CIE archiviert.

1. INTRODUCTION

It is widely recognized that colour-imaging workflows that use colour encodings based on a physically realizable device, such as that defined by sRGB (IEC 61966-2-1) or SWOP CMYK (ANSI/CGATS TR 001), may unduly restrict the gamut of encodable colours for some applications. This has prompted the development of several extended-gamut colour encodings, such as sYCC (IEC/ISO 61966-2-1 A1), bg-sRGB (IEC/ISO 61966-2-1 A1), bg-sYCC (IEC/ISO 61966-2-1 A1), ROMM RGB (ANSI/I3A IT10.7666), and others. One of the common characteristics of these extended-gamut colour-encoding specifications is that they all pose the capability to encode colours that are more chromatic than the gamut of any particular device, such as a standard sRGB display. With this plethora of options available for storing, interchanging and manipulating extended-gamut digital images, the issue then becomes how to identify the alternative encoding that best satisfies the needs of a particular application.

The goal of this document is to define a set of objective metrics for evaluating the characteristics of output-referred¹ extended-gamut² colour encodings. While it is not the intent of this document, nor of this CIE Technical Committee, to make a recommendation as to which colour encoding should be adopted for use in any particular application, it is anticipated that the recommended metrics presented here will be used by other standards groups in the process of identifying colour encodings appropriate for various industries and workflows.

Detailed metrics have been developed to evaluate a number of important attributes of extended-gamut colour encodings. These criteria include:

- gamut volume characteristics,
- colour quantization characteristics,
- hue constancy when applying non-linear tone scale modifications to RGB colour values,
- complexity of transformation required to and from typical standard spaces (sRGB, ICC PCS, etc.).

A number of other criteria have also been identified that may be important for some applications, although detailed metrics have not been defined at this time. These criteria include:

- perceptual isometry (visual uniformity),
- compressibility,
- compatibility with existing industry practice (e.g., ICC colour management, Adobe Photoshop software, etc.).

Each of these criteria addresses an important aspect of colour encoding performance that should be considered when selecting a colour encoding for use in a particular application. The relative importance of any one criterion however, will be a function of the application. In general, it is doubtful that any single colour encoding is going to optimally satisfy the requirements of all applications. While these criteria do not exhaust the issues that should be considered in the design of a digital imaging workflow, they should provide a reasonable starting point for selecting an appropriate colour encoding.

This document is broken down into a series of sections dealing with each of the criteria for which detailed metrics have been developed. In Section 2 a set of colour gamut metrics are defined which are designed to measure the effectiveness of a colour encoding for representing various sets of important colours. In Section 3 quantization accuracy tests are presented that quantify the magnitude of quantization errors that can be expected when representing colours in a colour encoding. Section 4 describes a metric that can be used to characterize hue constancy when applying non-linear tone scale modifications to RGB colour values. Section 5 examines the complexity of transformation to/from various important colour encodings. Finally, Section 6 documents a set of additional criteria relating to colour encoding

¹ Per ISO 22028-1, output-referred image data represents the colour-space coordinates of the elements of an image that has undergone colour rendering appropriate for a specified real or virtual output device and viewing conditions.

² Per ISO 22028-1, extended-gamut colour encodings have a colour gamut extending outside that of the standard sRGB CRT display as defined by IEC 61966-2-1.

attributes that may be important for some applications, but for which detailed metrics have not yet been defined.

2. COLOUR GAMUT METRICS

A series of four colour gamut metrics were developed to quantify the colour gamut sizes of various colour encodings and to compare their ability to encode sets of important colours (referred to as *target* colours). These metrics are:

1. total CIELAB³ gamut volume of the colour encoding for legal colours,
2. percentage of target colour gamut contained within colour encoding,
3. percentage of colour encoding gamut volume used to encode target colour gamut,
4. percentage of colour encoding code values used to encode target colour gamut.

This section is broken down in to three parts. Gamut descriptors for the target colour gamuts used in this study are defined in Section 2.1. Section 2.2 describes the process of defining a gamut descriptor for a colour encoding. Section 2.3 details the four recommended gamut metrics and provides example calculations for six extended-gamut output-referred colour encodings. Of these metrics, the two that are believed to provide the greatest insight into colour encoding performance are Metrics 2 and 4.

2.1 Target colour gamut definitions

Several of the metrics developed in this section are designed to quantify the appropriateness of an extended-gamut colour encoding for encoding specific sets of target colours that are relevant for various applications. For the purposes of this evaluation, the following sets of target colours were defined:

- real-world surface colours,
- optimal surface colours,
- legal colours,
- CRT colours (as defined by sRGB),
- photographic print colours.

The real-world surface colour gamut was defined by fitting a convex hull to a set of 1739 measured surface colour patches including; a set of non-fluorescent Munsell samples from the Colour-Cascade set; a set of surface colours measured by Trussel from North Carolina State University; a set of DuPont paint samples (measured by RIT); and a set of graphic arts spot colours⁴. Of these 1739 colours, 193 were on the surface of the convex hull. The resulting convex hull representing the real-world surface colour gamut is shown in Fig. 2.1(c). (The gamut surface can be defined by a list of the CIELAB vertices for the 193 colours on the surface of the gamut⁵, together with a triangle facet list identifying the vertices for each triangle.)

While the real-world surface colour gamut is intended to represent the surface colours commonly encountered in nature, the optimal surface colour gamut represents the

³ The CIELAB colour space was selected as the uniform colour space to perform comparisons between the different colour encoding specifications. While CIELAB has many documented limitations, it continues to be the most widely used uniform colour space for imaging systems evaluation and device-independent colour management. In particular, the ICC PCS encoding of the CIELAB colour space (with its associated reference viewing environment, and implicit reference imaging media) was selected for these comparisons based on its widely accepted use as an output-referred colour interchange space and its well-defined relationship to many of the colour encoding specifications tested.

⁴ Note that the real-world surface colour and the photographic print colour gamuts do not represent theoretical limits, but rather are representative examples of such gamuts. For some applications, it may be desirable to supplement these data sets with additional colours, or to use alternative data sets.

⁵ The CIELAB values for the patch colours were normalized in a way so as to be consistent with the ICC PCS CIELAB encoding [as defined in ICC.1:2001-04, (ICC, 2001a)].

theoretical gamut for surface colours that can be formed from idealized block dyes. The optimal surface colour gamut for CIE Illuminant D50 was calculated using the algorithm described by MacAdam (1935a,b). The details of this algorithm are shown in Appendix A of this document. The optimal surface colour gamut is formed from a set of idealized block reflectors. These block reflectors consist of both band-pass and band-block types. A series of optimal colour stimuli were calculated for luminance factors spanning the dynamic range of the ICC PCS reference medium⁶. The block reflector spectra were converted to CIE 1931 XYZ values for CIE Illuminant D50. The CIE XYZ values were converted to PCS CIELAB values, and were used to form a tessellated gamut descriptor, [see Fig. 2.1(d)], using a 3-dimensional α -shapes operation similar to that described by Cholewo and Love (1999) using a value of 30 for α .

The legal colour gamut represents another theoretical gamut comprising all colours falling within the spectrum locus. This would include not only the gamut of surface colours, but would also encompass self-luminous sources, and represents a hard boundary limit beyond which there is no physically realizable colour. This colour gamut is similar to those shown by Wyszecki and Stiles [1982, p. 167, Fig. 2(3.3.9)]. In this case, the range of luminance factors for which the gamut was calculated was limited to that of the PCS reference medium. The legal colour gamut used in this study is shown in Fig. 2.1(e)⁷. While it is unlikely that many of the extreme colours included in the optimal surface colour gamut and the legal colour gamut would ever be encountered in a real imaging system, they serve as useful limiting cases for testing worst-case encoding scenarios.

The gamut of photographic print colours was constructed from sets of dye spectra representing common commercial photographic print papers from three different manufacturers. A photographic paper model was used to determine the CIELAB values for a CMY lattice of analytical dye densities for each of the sets of dye spectra. (The maximum and minimum densities of the modelled photographic paper were chosen to be consistent with the PCS reference medium). A convex hull was then calculated that enclosed the data for all of the dye sets. The PCS CIELAB representation of this gamut is shown in Fig. 2.1(a).

For defining the gamut of typical CRT colours, the sRGB colour encoding was utilized. A gamut surface descriptor for sRGB was created by processing an 18^3 lattice of code values through the sRGB equations to produce corresponding CIE 1931 XYZ values. The white point for sRGB is defined to have the chromaticity of CIE Standard Illuminant D65. Since the white point of the ICC PCS is defined to have chromaticity of CIE Illuminant D50, the sRGB XYZ values were chromatically adapted to produce a corresponding set D50 XYZ values that would have approximately the same colour appearance in the ICC PCS viewing environment as the D65 XYZ values would have in the sRGB viewing environment. The chromatic adaptation consisted of cone space Von Kries normalization using the

⁶ The Version 2 PCS CIELAB encoding defined in ICC.1:2001-04 was used for this analysis. Since this version of the ICC profile specification did not include a precise definition of a PCS reference medium however, the reference medium associated with the Version 4 PCS definition given in ICC.1:2001-12 (ICC, 2001b) was assumed.

⁷ It is interesting to note that it was not necessary to have a 3-dimensional CIELAB representation of the spectrum locus gamut in order to determine if a colour point was within the spectrum locus. This could easily have been performed using a 2-dimensional convex hull of the chromaticities of the spectrum locus. For the purposes of the metrics presented here however, the 3-dimensional CIELAB representation was useful for consistency with the other sets of target colours. These legal colour gamut data were also used for several other purposes. For example, some of the PCS CIELAB values fall outside of the spectrum locus. As such, in the gamut volume calculations for PCS CIELAB, these regions did not represent valid colours, and were therefore eliminated from the calculations by gamut mapping the nodes of the PCS CIELAB gamut surface descriptor to the legal colour gamut while maintaining lightness and hue.

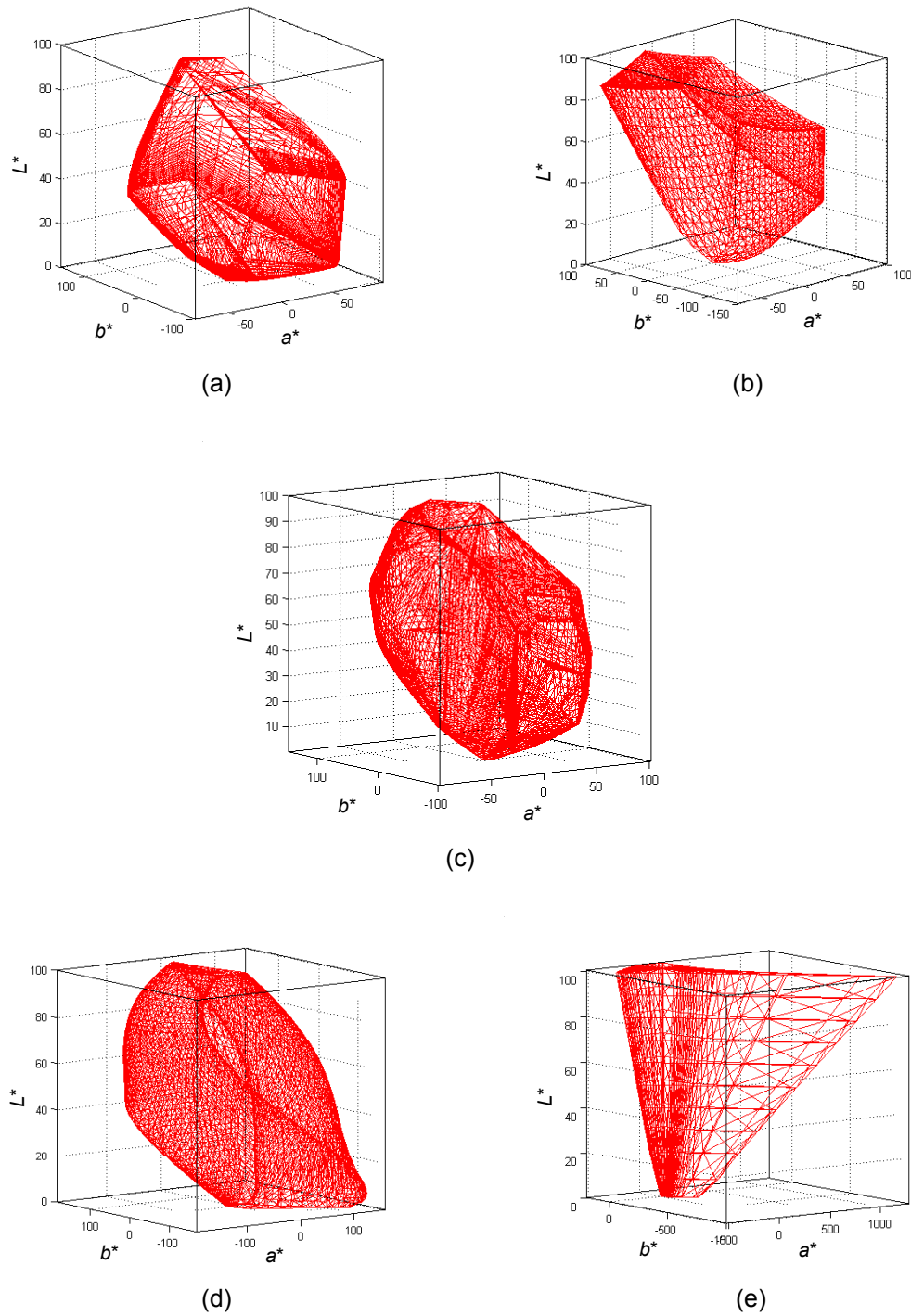


Fig. 2.1. Gamut surface descriptors for (a) gamut of photographic print colours, (b) sRGB gamut, (c) the gamut of real-world surface colours, (d) optimal surface colour gamut (for CIE Illuminant D50), and (e) legal colour gamut defined by the spectrum locus.

Hunt-Pointer-Estevéz cone fundamental matrix (Fairchild, 1998).⁸ It was assumed that all other differences in the viewing environments could be neglected. In addition, the white and black points of the sRGB colour encoding were assumed to be equivalent to that of the PCS reference medium, thus no dynamic range compression or clipping was needed to fit the encoding dynamic range into the PCS. This approach is consistent with common practice in colour-managed workflows, and is similar to that outlined by Nielsen and Stokes (1998) where it was proposed that the flare corrections and viewing condition transformations from the monitor viewing space to the hardcopy viewing conditions roughly cancel each other out. (Note that this same approach was used for all calculations in this report for all of the colour encodings that are based on the sRGB colour encoding - i.e., sRGB, bg-sRGB, sYCC, and bg-sYCC.) The resulting sRGB gamut surface is shown in Fig. 2.1(b).

It should be noted that the use of a chromatic adaptation transform to convert from the D65 sRGB viewing environment to the D50 ICC PCS viewing environment represents a special case of using a colour appearance model to transform from an input viewing environment to a reference viewing environment; this simplification is appropriate if the only significant difference in the viewing environments is the adapted white point. The more general case of using a full colour appearance model is illustrated in Fig. 2.2. Given a first set of input colour values ($XYZ_{1,D65}$) associated with a first D65-based viewing environment, and a second set of input colour values ($XYZ_{2,D50}$) associated with a D50-based reference viewing environment, it would not be appropriate to compute colour differences by directly comparing CIELAB colour values calculated relative to the input white points since corresponding colours will not have the same CIELAB values. Rather, a colour appearance model (CAM_{D65}) can be used to estimate the colour appearance corresponding to the first set of input colour values (JAB_1). An inverse colour appearance model (CAM_{D50}^{-1}) can then be used to determine corresponding colour values that would produce the same colour appearance in the reference viewing environment. Since the two sets of colour values ($XYZ_{1,D50}$ and $XYZ_{2,D50}$) are now defined relative to the same viewing environment, it is valid to compare them using conventional colour difference metrics such as ΔE^* . For the case where the only viewing environment attributes that differ are the adapted white points, then it can be seen that the forward/inverse colour appearance models reduce to a simple chromatic adaptation step ($CAM_{D65 \rightarrow D50}$) as was assumed for the example calculations given in this technical report.

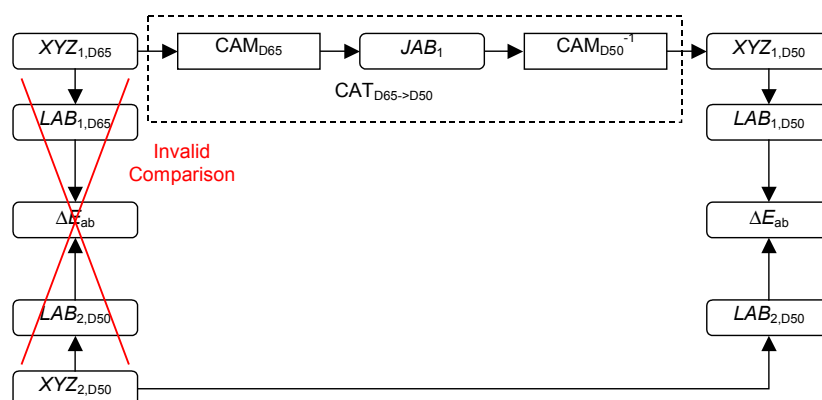


Fig. 2.2. Use of a colour appearance model to convert input colorimetry in a D65 viewing environment to a set of corresponding colorimetry in a reference D50 viewing environment. This enables a valid comparison of colorimetry that is intended for different viewing environments.

⁸ The Hunt-Pointer-Estevéz cone fundamental matrix was selected for these example calculations based on its widespread use. Clearly, the specific forms of the optimal cone fundamental matrix and chromatic adaptation process are subjects for considerable debate. It was neither the goal of this TC nor of these colour gamut metrics to address these complex issues. Fortunately, the exact form of the chromatic adaptation transform is less of an issue for these metrics than for complex appearance modelling tasks. The volumes of the gamuts formed by these corresponding colours should not change significantly with changes in the definition of the chromatic adaptation transformation. It is recommended however, that the same chromatic adaptation transform be used throughout the analysis.

2.2 Colour encoding gamut descriptors

To define a colour gamut descriptor for a colour encoding, a tetrahedral tessellation of an 18^3 grid of device code values is transformed from device code values to corresponding CIELAB colour values (in particular, PCS CIELAB). The tessellation of the grid of device code values has an inherent connectivity based on the proximity of points in the lattice. As such, a tetrahedral partitioning of the code value lattice is known a priori. When the transformation from device code values to CIELAB is continuous and invertible, the tetrahedral partitioning of the code value lattice remains topologically consistent in the CIELAB colour space. As such, no repartitioning is necessary.

Partitioning the gamut into a set of tetrahedral regions has the advantage of easy volume calculation and easy point-in-gamut calculations. Using the tetrahedral partitioning, total gamut volume is calculated by summing the volumes of each tetrahedron. The point-in-gamut problem reduces to testing each tetrahedron to determine if the point falls inside one of them. By definition, a set of four non-coplanar points in a three-dimensional space (e.g., PCS CIELAB) defines a convex polyhedron. Many algorithms are available for determining inclusion of a point within a convex polyhedron. In the case of the tetrahedral partitioning used in these gamut descriptors, the set of tetrahedron define a simplicial complex (i.e., they are all connected to form a contiguous object). Each tetrahedron (simplex) defines a local basis that can be tested for the inclusion of the test point. Other techniques such as edge crossings could be used to determine the inclusion of a point in a convex set (Goodman and O'Rourke, 1997). For the purpose of this document a process similar to the point-in-polygon process described in Hung (1993) was used.

An example tessellation of a colour encoding space code value cube is shown in Fig. 2.3. This example shows a 5^3 lattice of sRGB code values transformed into PCS CIELAB colour values. (While the example uses a 5^3 lattice for illustration purposes, 18^3 lattices are recommended for the metrics described in this document.) Using this method, creation of the sRGB, ROMM RGB, and PCS CIELAB gamut descriptors, shown in Fig. 2.4, was straightforward, since each of these colour encodings has a continuous and invertible relationship with the PCS CIELAB. (Albeit, the D65 sRGB colorimetry needed to be chromatically adapted to Illuminant D50 as was discussed above.)

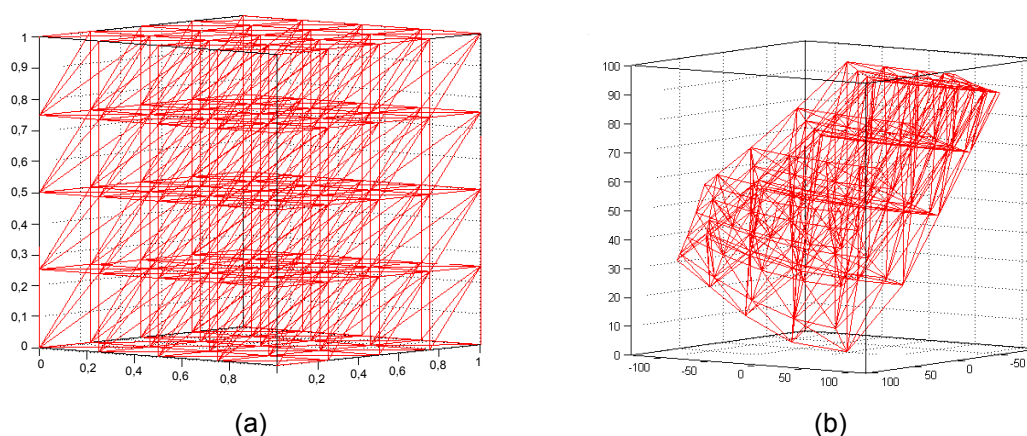


Fig. 2.3 Illustration of colour gamut descriptor based on transforming a tetrahedral partitioning of a normalized code value lattice (a) into its corresponding PCS CIELAB form (b).

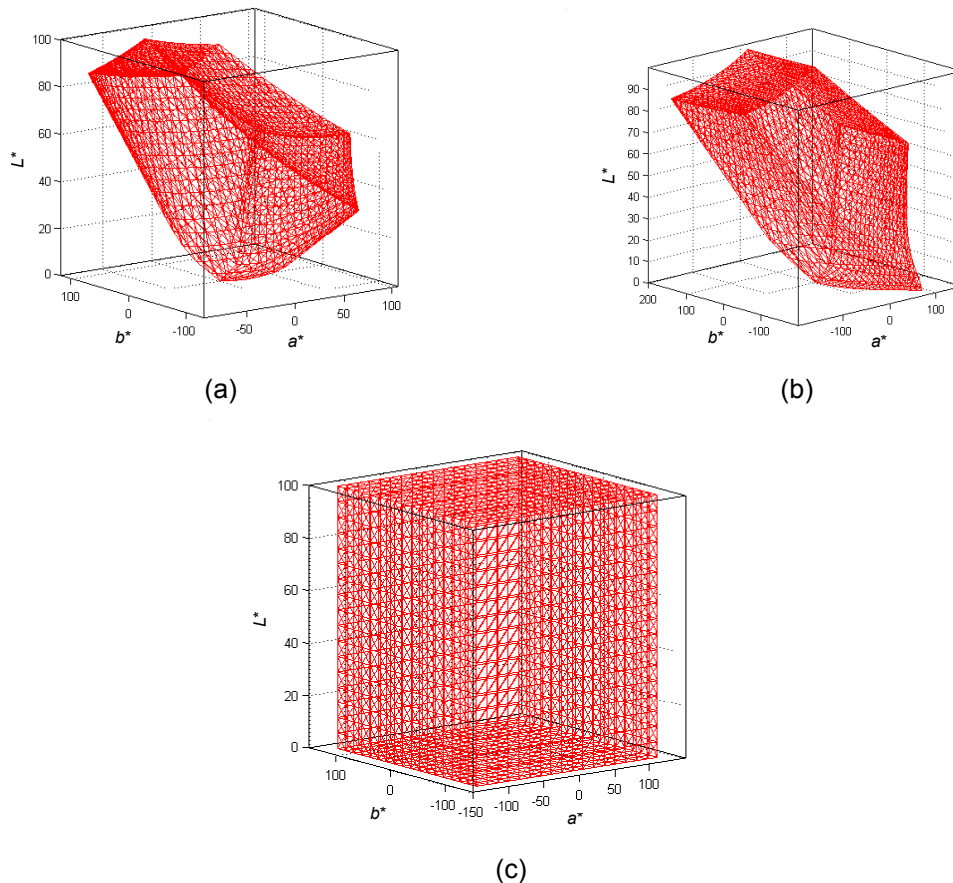


Fig. 2.4 PCS CIELAB gamut surface descriptors for (a) sRGB, (b) ROMM RGB, and (c) PCS CIELAB.

The colour gamut descriptors created for the sYCC, bg-sRGB, and bg-sYCC colour encodings were not as straightforward to generate. This is because they do not possess a well-defined invertible relationship between the code values of the encoding space and CIELAB throughout some of the extended portions of their colour gamuts. This stems from the fact that their encoding equations, which relate the code values to CIE colorimetry, can result in negative CIE XYZ tristimulus values. These negative tristimulus values then need to be converted into CIELAB values using the CIE 1976 $L^*a^*b^*$ equations. The CIE 1976 $L^*a^*b^*$ equations make no provision for colours having negative tristimulus values. (Negative tristimulus values are outside of both the spectrum locus and the CIE 1931 XYZ primary set. As such, they are outside the realm of normal trichromatic human colour vision.)

One option in treating these negative tristimulus values is to clip them to zero before they are converted to CIELAB values. Recall however, that in order for the code value tetrahedral partitioning to be a valid tessellation in the CIELAB space the transformation from code values to CIELAB needs to be continuous and invertible. Clipping violates this constraint. Also, for reasons that relate to gamut volume, it is undesirable to clip these values to zero because it artificially deflates the gamut volume of these colour encodings. This could in turn, bias their rankings in some of the gamut metrics described below.

In order to compute CIELAB values (admittedly artificial ones) for colours with negative tristimulus values, an extension was made to the CIE 1976 $L^*a^*b^*$ definition. Recall that the CIELAB equations are given by:

$$L^* = 116 \cdot f\left(\frac{Y}{Y_n}\right) - 16 \quad (2.1)$$

$$a^* = 500 \cdot \left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right) \right] \quad (2.2)$$

$$b^* = 200 \cdot \left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right) \right] \quad (2.3)$$

$$f(\varpi) = \begin{cases} (\varpi)^{\frac{1}{3}} & \varpi > \left(\frac{24}{116}\right)^3 \\ \frac{841}{108} \cdot (\varpi) + \frac{16}{116} & \varpi \leq \left(\frac{24}{116}\right)^3 \end{cases} \quad (2.4)$$

where X_n , Y_n , and Z_n are the tristimulus values of the reference white. In order to accommodate negative tristimulus values the relationship shown in Eq. (2.4) was extended to:

$$f(\varpi) = \begin{cases} (\varpi)^{\frac{1}{3}} & \varpi > \left(\frac{24}{116}\right)^3 \\ \frac{841}{108} \cdot (\varpi) + \frac{16}{116} & \left(\frac{24}{116}\right)^3 \geq \varpi \geq -\left(\frac{24}{116}\right)^3 \\ -(\varpi)^{\frac{1}{3}} & \varpi < -\left(\frac{24}{116}\right)^3 \end{cases} \quad (2.5)$$

for the a^* and b^* equations and the L^* relationship was extended to:

$$L^* = \begin{cases} 116 \cdot \left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - 16 & \frac{Y}{Y_n} > \left(\frac{24}{116}\right)^3 \\ 116 \cdot \frac{841}{108} \cdot \left(\frac{Y}{Y_n}\right) & \left(\frac{24}{116}\right)^3 \geq \frac{Y}{Y_n} \geq -\left(\frac{24}{116}\right)^3 \\ -\left(116 \cdot \left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - 16\right) & \frac{Y}{Y_n} < -\left(\frac{24}{116}\right)^3 \end{cases} \quad (2.6)$$

Modifying the CIELAB equations in the manner shown in Eqs. (2.5) and (2.6) has the effect of mirroring the nonlinearities in the CIELAB equations about their respective origins. (Recall, this process was formulated purely for computational purposes to allow for the comparison of colour encodings that include colour values corresponding to non-physical colours. The CIELAB values corresponding to negative XYZ values should not be interpreted to have any perceptual significance, and are not recommended for any other purpose beyond the computation of the metrics defined in this report.) Based on these modified CIELAB equations the gamut surface descriptors for bg-sRGB, sYCC, and bg-sYCC are shown in Fig. 2.5. Notice the negative lightness values and the odd behaviour for some high chroma colours.

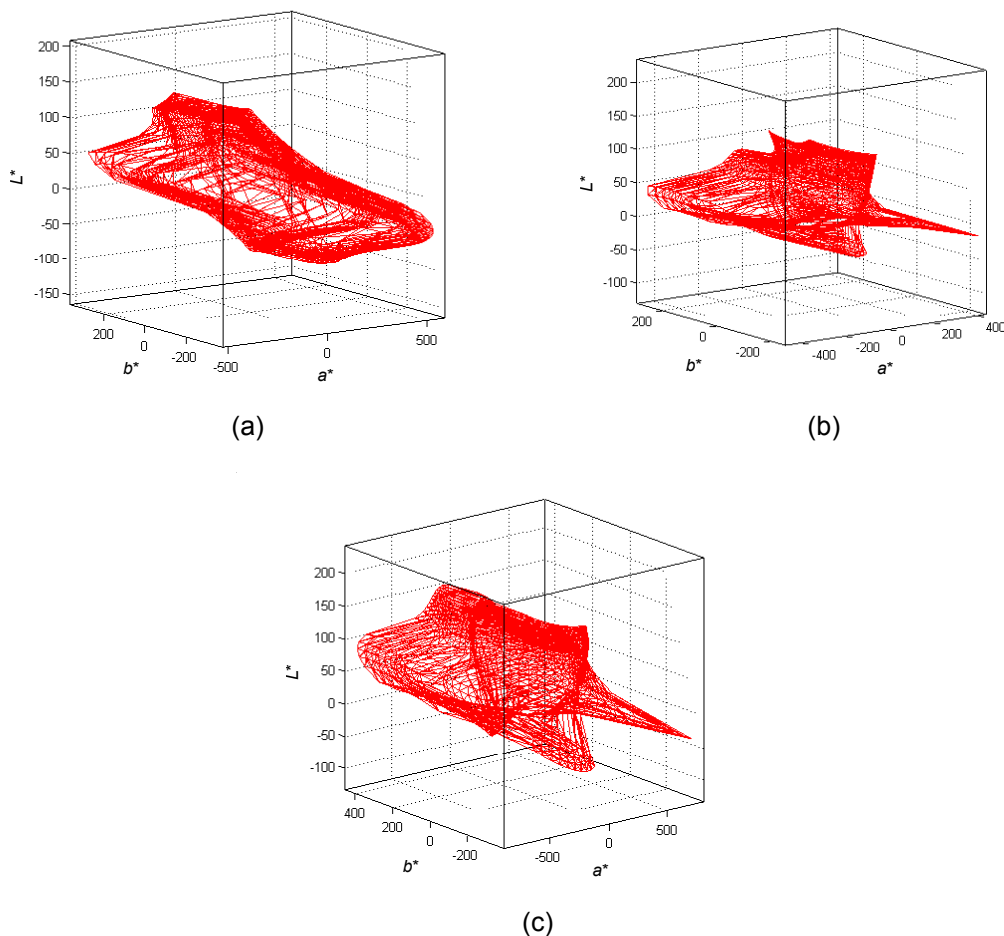


Fig. 2.5. ICC PCS gamut surface descriptors for bg-sRGB (a), sYCC (b), and bg-sYCC (c).

2.3 Colour gamut metric definitions

The following sections detail the metrics developed for comparing the colour gamuts of output-referred colour-encodings. Each section comprises:

- a metric description section,
- a target metric value section identifying the optimal value for the metric,
- a technique description section that gives a high-level description of the process used to compute the metric,
- a details section that gives a step-by-step description of the process used to compute the metric value (generally the details section includes flowcharts and other descriptive text that outlines the computational process) and
- an example metric calculation section that gives example metric values computed for the six colour encodings evaluated throughout this document.

2.3.1 Metric 1: Colour encoding gamut volume

The first colour gamut metric considered is the total CIELAB gamut volume encompassed by the colour encoding. A detailed flowchart illustrating the algorithm used to create the gamut and calculate the CIELAB volume is shown in Fig. 2.6. For this metric, any colours outside the gamut of legal colours are eliminated to account for the inflated gamut volumes of some of the colour encodings that resulted from the fact that certain code value combinations correspond to imaginary colours outside the spectrum locus. Also, any regions of colour space that were explicitly defined to be illegal by the colour encoding specification were also eliminated from the colour gamut volume calculation. Recall that a given colour encoding space was

represented by a tetrahedral complex in the ICC PCS space. Any of the tetrahedra containing illegal colours were then truncated accordingly, and the gamut volume was computed by summing the volumes of each tetrahedron⁹. The volume of a tetrahedron was calculated by taking one sixth of the volume of the parallelepiped created by the vector space formed by the four points of the tetrahedron:

$$t_{\text{vol}} = \frac{1}{6} \begin{vmatrix} p_1(L^*) - p_0(L^*) & p_1(a^*) - p_0(a^*) & p_1(b^*) - p_0(b^*) \\ p_2(L^*) - p_0(L^*) & p_2(a^*) - p_0(a^*) & p_2(b^*) - p_0(b^*) \\ p_3(L^*) - p_0(L^*) & p_3(a^*) - p_0(a^*) & p_3(b^*) - p_0(b^*) \end{vmatrix} \quad (2.7)$$

where || represents the determinant of the matrix representing the vector space formed by the four PCS CIELAB vertices of the tetrahedron $\{p_0, p_1, p_2, p_3\}$

Metric

Cubic CIELAB volume.

Target metric value

This metric does not have a clear optimal metric value, and may therefore have limited usefulness in many applications. Generally, bigger gamuts will be able to represent more colours, but this is only valuable if the colours are those that would be encountered in a particular application. Colour encodings having gamuts that are unnecessarily large will result in larger than necessary quantization errors. For this reason, the gamut volume metrics that compare the gamut of the colour encoding to a set of colours of interest in a particular application (Gamut Metrics 2-4) will generally be more useful.

Technique

Summed tetrahedral volumes.

Details

The gamut boundaries are characterized using a lattice of code values that span the range of the encoding. The lattice is broken into tetrahedra, and the sum of the tetrahedra volumes is computed.

1. The tetrahedral connectivity of the lattice points is known from the proximity of the points in the code value lattice. Two sets of data are supplied.
 - Code value lattice data: the code value points within the lattice—3 columns by the number of points in the lattice (by default, the lattice size will be 18×18×18).
 - Tetrahedral connectivity list: 4 columns by the number of tetrahedron in the lattice data set (by default, the number of tetrahedra = 17×17×17×6 = 29478). Each of the columns stores the indices of the four points that make up a given tetrahedron. (These indices reference points in the code value lattice data set.)
2. Convert each code values lattice point into XYZ colorimetry according to the colour encoding specification of the colour encoding being evaluated.

⁹ The process used to truncate the illegal vertices of a tetrahedron consisted of gamut mapping the illegal vertex onto the limiting gamut (e.g., ICC PCS) using hue-and-lightness preserving chroma clipping. In some cases this process can cause the topology of the tetrahedron to invert – e.g., when one or more of out-of-gamut vertices of the tetrahedron were mapped to chroma values less than the in-gamut vertices. The volume of the resulting tetrahedron is not representative of a real volume. As such, these tetrahedra were removed from the gamut volume calculations. This will result in slightly underestimated volumes for some colour encoding specifications. An alternative process might have been to map these vertices back to the reference gamut using a process that maintains the topology of the tetrahedron. This phenomenon is most likely to occur in regions of colour space where the chroma of the reference gamut boundary varies rapidly with changes in hue angle.

3. If necessary, apply a chromatic adaptation transformation to D50 XYZ colorimetry using a von Kries chromatic adaptation with the Hunt-Pointer-Estevéz cone primaries matrix. (A colour appearance model, such as CIECAM02, could also be used if the specified viewing conditions for the different colour encodings are significantly different.)
 - For output-referred colour encodings, the tristimulus values should be normalized such that the XYZ values intended to be mapped to the black point of the ICC PCS are mapped to $Y=0$, and the XYZ values intended to be mapped to the white point of the ICC PCS are mapped to $Y=100$.
4. Convert the D50 XYZ values to CIELAB using a D50 XYZ with $Y=100$ as the white-point normalization.
5. Check colour values of vertices to determine if any correspond to illegal colours. (Illegal colours are those that are outside the spectrum locus, or any other illegal colour regions defined by the colour encoding specification. For example, some encodings specify that colours should be within the ICC PCS. One convenient means for performing this test is to form a hull of legal colours and then check each vertex to see whether it is inside the hull.)
6. Form tetrahedra using the lattice of CIELAB values and the tetrahedral connectivity list.
7. Eliminate any tetrahedra where all vertices are an illegal colour.
8. For tetrahedra containing some legal vertices and some illegal vertices, the colour values for the illegal vertices should be clipped to the legal limit.
9. Calculate the volume of each tetrahedral gamut element. This calculation is done by taking $1/6^{\text{th}}$ of the value of the determinant defined by the vector space formed by the tetrahedron, accounting for the offset.
10. Sum up the volumes of all the tetrahedron to determine the total gamut volume in cubic CIELAB units.

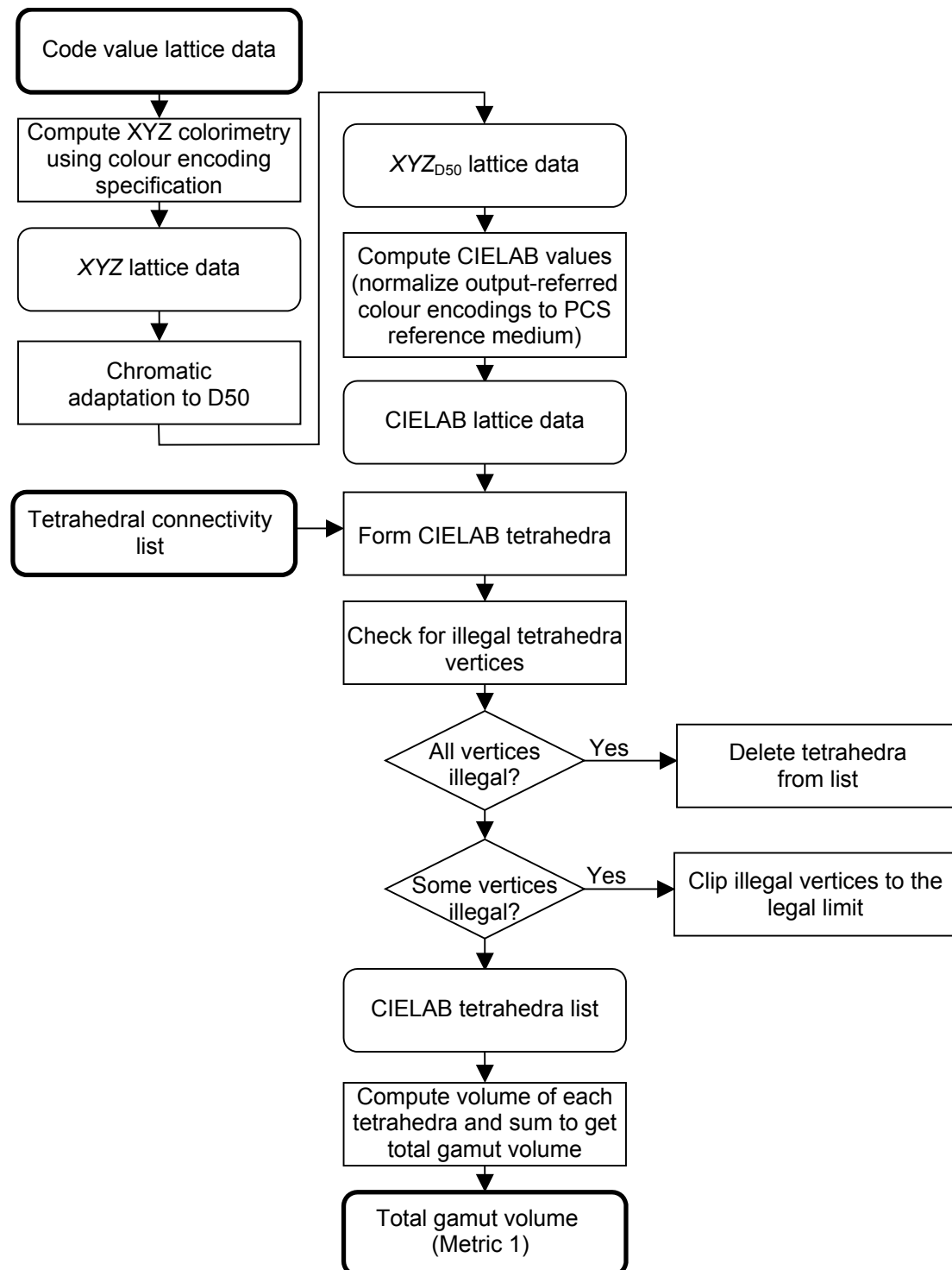


Fig. 2.6. Method for calculating total colour gamut volume (Metric 1).

Example metric calculations

The results of total gamut volume, shown in Table 2.1, indicate that all the extended-gamut colour encodings have significantly larger colour gamuts than sRGB. As expected the YCC based colour gamuts (sYCC and bg-sYCC) are larger than their RGB based counterparts (sRGB and bg-sRGB). (Not surprisingly, as shown in the next sections, these colour encodings pay a quantization price for their extra gamut.)

Table 2.1. Sample results for total legal colour gamut volume calculation.

Colour encoding	Total colour gamut volume (ΔE^3)
sRGB	821 000
sYCC	2 555 000
bg-sRGB	3 097 000
bg-sYCC	4 049 000
ROMM RGB	2 515 000
PCS CIELAB	4 081 000

While Gamut Metric 1 gives an indication of the total colour gamut associated with a colour encoding, it is difficult to draw conclusions from this metric alone. For many applications, bigger may not always be better if portions of the larger colour gamut never get used by any real colours that are likely to be encountered in that particular application. As a result, three additional gamut metrics were developed to answer the question of how well a particular colour encoding addresses a set of target colours that are important for a particular application.

2.3.2 Metric 2: Percentage of target colour gamut represented within colour encoding gamut

Gamut Metric 2 is computed by comparing the volume of the intersection of a particular target colour gamut and the colour-encoding gamut to the gamut volume of the target gamut:

$$p_2 = \frac{\text{vol}(\text{CES} \cap \text{T})}{\text{vol}(\text{T})} \quad (2.8)$$

where CES and T represent the gamuts of the colour encoding and the target colour gamut, respectively. The vol() process is a gamut volume operator that computes total volume by summing the volumes of each individual tetrahedron in the respective gamut volume. This metric is intended to give an indication of how fully the colour encoding covers the colours in the target colour gamut.

2.3.3 Metric 3: Percentage of colour encoding gamut volume used to encode target colour gamut

Gamut Metric 3 is computed by comparing the volume of the intersection of the target gamut and the colour-encoding gamut to the volume of the colour-encoding gamut:

$$p_3 = \frac{\text{vol}(\text{CES} \cap \text{T})}{\text{vol}(\text{CES})} \quad (2.9)$$

This metric was intended to give an indication of how much of the colour encoding gamut is used by the colours in the target colour gamut. It was found however, that the results of this calculation are sometimes misleading due to the fact that the colour encoding gamut may be artificially large for some of the extended-gamut colour encodings due to the distortions introduced for colours corresponding to negative tristimulus values, etc. This led to