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Television colorimetry elements

BT Series

Broadcasting service (television)

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Television colorimetry elements

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Introduction

The purpose of a television system is to give to the viewer the possibility of viewing scenes from a distant time or place. It is thus important that it allows the maximum possible similarity of reproduced image and original scene, and also maximum creative freedom for programme makers to choose the look of the programme.

With use of digital technologies, distortion of a video bit stream itself can be insignificant, but the potential sources of distortions include colour rendering when shooting, in transmission and in reproduction equipment, and image processing and coding systems.

The transmission of colour information in existing systems is based on colorimetric principles. The main way to improve current the viewer's experience is by taking greater account in capturing and transmission of visual perception characteristics and viewing conditions.

The accumulated knowledge of visual perception mechanisms and characteristics, including colour perception and display, serve as the basis for progress in image system fidelity.

The starting point for colorimetric calculations is the XYZ system adopted by the international commission on illumination (CIE) in 1931. This is a coordinate system that describes spectral colour perception using a colour space. As a means of specifying colorimetry, one of the drawbacks of the system is that it does not take into account adaptation and observation conditions of the human vision system. This system does not exhibit uniform 'distances' between the equally perceptible colour differences across the colour space.

Two systems or diagrams, each with advantages, which had uniform spacing of perceived differences, CIELUV and CIELAB systems, were adopted by the CIE in 1976. The CIELUV system uses a MacAdam uniform colour scale, using experimental data for threshold colour differences. The CIELAB system uses a cube root formula to derive colour coordinates.

CIELUV system has largely found use for television applications, and CIELAB system has largely found use for multimedia and other applications.

One of the recent achievements of colorimetric science is the development of the CIECAM02 colour appearance model, which is consistent with experimental data on colour perception. It is now recommended for colour management by the CIE. In this system, real colour perception mechanisms are taken into account, including adaptation properties.

Some modifications of CIECAM02, to enhance uniformity and to account for spatial and temporal vision effects, are described in this handbook.

Colorimetry of television and other electronic image systems is based on the use of signals that can be associated with colour space coordinates within the system and coordinate-dependent transmitted scene and reproduced images. This association is realized with source camera and reproducing device. Currently the account taken of vision characteristics is a simplified one.

In the image systems used for different applications, the option of similarity of image colour obtained in shooting and in reproduction environment is essential. The International Colour Consortium (ICC) has agreed general principles of colour rendering, according to which all colorimetric transformations should be realized in a single colour space, not dependent on the device types used, and in this space transformations for device matching should be applied.

Use of current colour perception models in television and related applications should form the basis for the following:

- Increasing of the colour reproduction quality by achievement of better similarity of the transmitted scene visual colours and reproducible image colours;
- Further coding efficiency increase with video information compression taking into account both current colour perception models and transmitted scene types information, and also statistics of colour image composition, detail and other characteristics of transmitted scenes;
- Improvement of colour reproduction quality assessment methods by using better human colour perception considerations;
- Perfection of television 'qualimeters' by the use of more perfect components, based on the use of current colour perception models and more common vision models;
- Optimal image quality management.

The advent of new components in television systems, and improvements in system models, may result in transformations of increasing complexity. This will become more practical with the evolution of integrated circuit technology.

At different stages of development, systems having different accuracy levels may be possible. A major new step in image system progress could be possible when and if MPEG-21 metadata information is used.

An important task is the achievement of backward compatibility of new systems with former systems. It may be achieved in television and related applications when innovation is such that systems operate according to former standards but include the option of new components giving additional opportunities that are not compatible with the old systems. In some cases, the backwards compatibility may limit quality and mean that certain quality levels never become available.

At the current stage of technical progress of image systems, enhancements of the colorimetry system are already embodied in UHDTV systems, in digital cinema, and ACES large screen digital imagery systems, in such image applications as Adobe Wide Gamut and Kodak RIMM-ROMM, and in multi primary display systems. Improvement is towards a wider colour gamut, image contrast enlargement, and colour accuracy enhancement. Some new applications such as using Free Scale-Gamut (FS-Gamut) and Free Scale-Log (FS-Log) opto-electronic transfer function are now possible.

In the sections of this Report, all these aspects, particularly, technical aspects correlated with colorimetry characteristics of TV and, to some extent, with other image systems, colour rendering quality aspects and aspects associated with the state-of-the-art of colour perception models, are considered.

CHAPTER 1

General model of light-to-light television and related imaging systems

Current television image systems can be represented as shown in Fig. 1.1. The end-to-end system is shown as a serial connection of light-to-signal conversion (via the camera), the electrical transmission path, and signal-to-light conversion (via the reproducing device).

In the electrical path of a television system, the transmitted signals are usually expressed as the R, G, B primary signals or $Y' \, C'_R \, C'_B$ luminance and colour difference signals. These signals can be considered as coordinates of the three-dimensional colour space of the system.

OETF (opto-electron transfer function) conversion and EOTF (electro-optical transfer function) conversion in the terminal devices may be represented as the transition from $S_1S_2S_3$ using non-constrained colour space coordinates (for example XYZ) to the constrained signals E_1, E_2, E_3 (for example R, G, B or $Y' \, C'_R \, C'_B$) on the transmission path, and as the transition from the signals E_1, E_2, E_3 to S_1^*, S_2^*, S_3^* coordinates of reproduced image colour space on the receiving side, which is constrained by the characteristics of the display.

Figure 1.2 is a block diagram of a potential adaptive image system, providing colour reproduction, independent of devices used (regarding any colorimetric transformations used in them). A principal distinction of such a system compared to a non-adaptive system may be the use of a colour space in the transmitting channel that is independent of the colorimetric transformations in devices used and independent of viewing conditions.

For colour reproduction quality assessment, a uniform colour space may be used, in which visual perception of object in the image is associated with the S_1, S_2, S_3 coordinates of this colour space at the transmitting side, and visual perception of reproduced image is associated with colour coordinates, S_1^*, S_2^*, S_3^* on the reproduction side.

S_1, S_2, S_3 colour spaces coordinates, expressed with different degree of accuracy with respect to the human vision, may be used. Colour spaces include those developed by the CIE: CIELUV, CIELAB, and CIECAM02. As a measure of colour reproduction quality in such a case, distances in the S_1, S_2, S_3 space may be used with appropriate conversion.

ICC (International Colour Consortium) has defined profiles for multimedia applications, independent of the capture and reproduction devices. For television, such an approach is not in current use; however, it may be desirable to develop systems independent of viewing conditions for any point of the light-to-light video chain (transmission path).

For television applications, these principles are described in [1.3–1.8].

FIGURE 1.1

Block diagram of a non-adaptive system

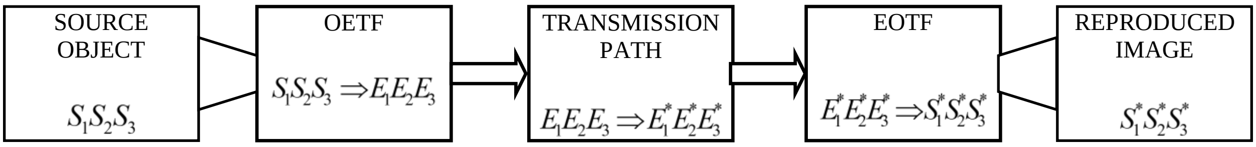
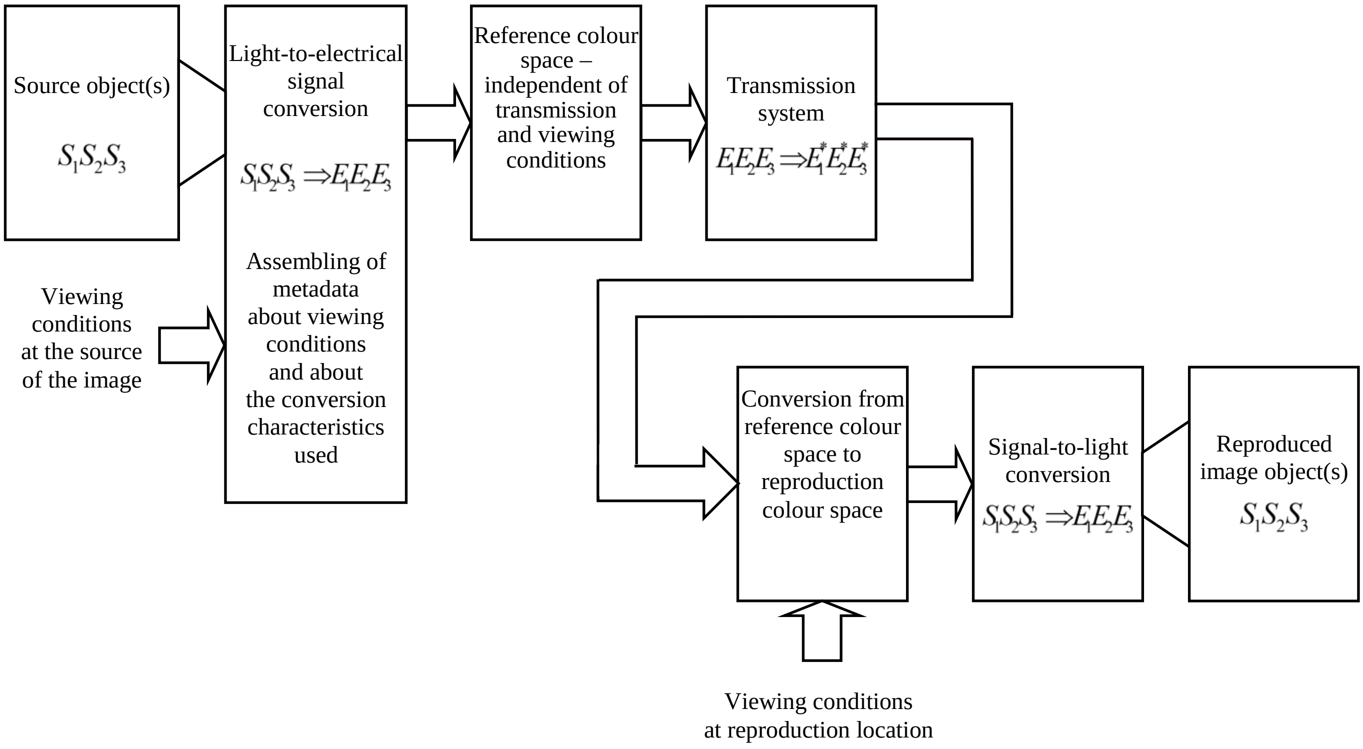


FIGURE 1.2

Block diagram of a potential adaptive system



CHAPTER 2

Colorimetric characteristics of television and related systems

2.1 Introductory note

Colorimetric characteristics have a major role in video systems characteristics; they considerably influence the overall quality of the transmitted and reproduced images. In this section information on colorimetric characteristics of television, multimedia and other related systems is summarized. The description of colour spaces for some image compression systems is also shown.

A complete colour space definition for digital video representation may include specification of the following aspects:

– The chromaticity coordinates $x_R, y_R, z_R, x_G, y_G, z_G, x_B, y_B, z_B$ of the source colour primaries R, G, B and coordinates x_W, y_W, z_W of reference white point.

– The opto-electronic transfer characteristics of the source components (e.g., definition of E'_R, E'_G and E'_B as a function of R, G and B).

– Matrix coefficients for transformation of the RGB components into luma and chroma components (e.g., definition of components E'_Y, E'_{C_B} and E'_{C_R} as a function of E'_R, E'_G and E'_B).

– Definition of scaling, offsets, and quantization for digital representation.

– A gamut boundary definition specifying the range of values over which effective representations of colours can be achieved.

2.2 Relationship between tristimulus values in *XYZ* colour space and in *RGB* signal space

The correlations interrelating between CIE-31 XYZ colour space and RGB signal space of TV system in accordance with SMPTE RP 177 [2.1] are represented in this subclause.

RGB signal space tristimulus values are normalized in such a way that reference white is equi-primary signal $(R = G = B = 1)$.

For transformations the $\mathbf{P}$ matrix of primaries chromaticity coordinates and $\overline{\mathbf{w}}$ vector of reference white chromaticity coordinates are used.

$$\mathbf{P} = \begin{bmatrix} x_R & x_G & x_B \\ y_R & y_G & y_B \\ z_R & z_G & z_B \end{bmatrix}; \qquad \overline{\mathbf{w}} = \begin{bmatrix} x_W / y_W \\ 1 \\ z_W / y_W \end{bmatrix} \tag{2.1}$$

The $\overline{\mathbf{w}}$ vector normalization corresponds to reference white assignment with a unit luminance factor.

Signal space in television is normalized to the unit range of relative luminance change that corresponds to change of R, G, B primary signal levels between the values 0 and 1. It corresponds to such XYZ space normalization that Y coordinate, characterizing the image relative luminance values, takes 0 values on black and 1 on white.

Relationship between CIE XYZ colour space and RGB signal space is carried out as

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \mathbf{NPM} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}; \qquad \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{NPM}^{-1} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}. \tag{2.2}$$

where the system primaries coordinates matrix is:

$$\mathbf{NPM} = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_R & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix} \tag{2.3}$$

It is calculated with use of formula:

$$\mathbf{NPM} = \mathbf{P} \cdot \mathrm{diag}\left(\mathbf{P}^{-1} \cdot \overline{\mathbf{w}}\right) \tag{2.4}$$

The second row of normalized system primaries coordinates matrix represents the vector of primaries luminance factors, relative colour luminance coordinates being determined as

$$Y = Y_R R + Y_G G + Y_B B. \tag{2.5}$$

Thus Y_R, Y_G, Y_B characterize primaries relative luminance. They are also named primaries luminance factors and designated:

$$L_R = Y_R, \quad L_G = Y_G, \quad L_B = Y_B.$$

It has been noted in [2.1] that as a result of calculations with the limited number of digits (because of rounding) coefficients of the second row can turn out in the calculation of **NPM** matrix, to give a sum that will differ from unity. In this case it is recommended to normalize the matrix columns so as to obtain this sum equal to unity.

The examples of colour space conversion of SDTV and HDTV signals from one colour space to another, based on formulas of direct conversion of R, G, B signals to X, Y, Z values and of inverse conversion of X, Y, Z values to R, G, B, signals, are presented in the Report ITU-R BT.2250 [2.31].

2.3 Colorimetric characteristics of digital standard definition and high definition television systems

Colorimetric characteristics of standard definition and high definition digital television systems are presented in Table 2.1, where:

L – relative luminance levels of R, G, B components

E' – gamma-corrected R, G, B signals relative levels (E'_R, E'_G, E'_B)

E'_Y – luminance signal;

E'_{CR} , E'_{CB} , E'_{PR} , E'_{PB} – colour-difference signals, normalized to the interval $\overline{-0.5; +0.5}$.

In Recommendation ITU-R BT.601-7 [2.4] 8 bit and 10 bit coded representation is used for digital SDTV systems and decimal values of the quantized signals are:

– for gamma-corrected R', G', B' signals:

$$R = \mathrm{int}\left\{\left(219E'_R + 16\right) \times D\right\} / D \tag{2.6}$$

$$G = \mathrm{int}\left\{\left(219E'_G + 16\right) \times D\right\} / D \tag{2.7}$$

$$B = \mathrm{int}\left\{\left(219E'_B + 16\right) \times D\right\} / D \tag{2.8}$$

TABLE 2.1

Colorimetric characteristics of standard definition and high definition digital television systems

<table>
<tr><th>System</th><th>Primaries and reference white chromaticity coordinates</th><th>Opto-electronic and electro-optic conversion characteristics</th><th>Coding equation</th></tr>
<tr><td>SDTV
(ITU-R BT.601-7 [2.4], item 3.6)</td><td>625/50/2:1<table><tr><th></th><th>x</th><th>y</th></tr><tr><td>Red</td><td>0.640</td><td>0.330</td></tr><tr><td>Green</td><td>0.290</td><td>0.600</td></tr><tr><td>Blue</td><td>0.150</td><td>0.060</td></tr><tr><td>White D_{65}</td><td>0.3127</td><td>0.3290</td></tr></table>525/60/2:1<table><tr><th></th><th>x</th><th>y</th></tr><tr><td>Red</td><td>0.630</td><td>0.340</td></tr><tr><td>Green</td><td>0.310</td><td>0.595</td></tr><tr><td>Blue</td><td>0.155</td><td>0.070</td></tr><tr><td>White D_{65}</td><td>0.3127</td><td>0.3290</td></tr></table></td><td>Opto-electronic conversion:
$E' = 1.099\,L^{0,45} - 0.099 \quad \text{for} \quad 0.018 \le L \le 1$
$E' = 4.500\,L \quad \text{for} \quad 0 \le L < 0.018$
Electro–optic conversion:
$L = \left[\left(E' + 0.099\right)/1.099\right]^{1/0.45} \quad \text{for} \quad 0.0812 \le E' \le 1$
$L = E'/4.500 \quad \text{for} \quad 0 \le E' < 0.0812$</td><td>$E'_Y = 0.299E'_R + 0.587E'_G + 0.114E'_B$
$E'_{C_R} = \left(E'_R - E'_Y\right)/1.402$
$E'_{C_B} = \left(E'_B - E'_Y\right)/1.772$</td></tr>
<tr><td>HDTV 1080 lines
with square active pixels
(ITU-R BT.709 [2.5])
HDTV 720 lines
(ITU-R BT.1543-1 [2.6], ITU-R BT.1847-1 [2.7])</td><td><table><tr><th></th><th>x</th><th>y</th></tr><tr><td>Red</td><td>0.640</td><td>0.330</td></tr><tr><td>Green</td><td>0.300</td><td>0.600</td></tr><tr><td>Blue</td><td>0.150</td><td>0.060</td></tr><tr><td>White D65</td><td>0.3127</td><td>0.3290</td></tr></table></td><td>Opto-electronic conversion:
$E' = 1.099L^{0,4500} - 0.099 \text{ for } 0.018 \le L \le 1$
$E' = 4.500L \text{ for } 0 \le L < 0.018$</td><td>$E'_Y = 0.2126E'_R + 0.7152E'_G + 0.0722E'_B$
$E'_{C_R} = \left(E'_R - E'_Y\right)/1.5748$
$E'_{C_B} = \left(E'_B - E'_Y\right)/1.8556$</td></tr>
</table>

– for luminance and colour-difference Y, C_R, C_B signals:

$$Y = \text{int}\{(219E'_Y + 16) \times D\} / D \tag{2.9}$$

$$C_R = \text{int}\left\{\left(224E'_{C_R} + 128\right) \times D\right\} / D \tag{2.10}$$

$$C_B = \text{int}\left\{\left(224E'_{C_B} + 128\right) \times D\right\} / D \tag{2.11}$$

where D takes either the value 1 or 4, corresponding to 8 bit and 10 bit quantization respectively. The operator $\text{int}(\ )$ returns the value of 0 for fractional parts in the range of 0 to 0.4999 … and +1 for fractional parts in the range 0.5 to 0.999 ..., i.e. it rounds up fractions above 0.5.

Recommendation ITU-R BT.601-7 specifies as well equations for derivation quantized luminance and colour-difference signals via quantized gamma-corrected R, G, B signals.

In Recommendations ITU-R BT.709-6 [2.5], ITU-R BT.1543-1 [2.6] and ITU-R BT.1847-1 [2.7] for digital HDTV systems 8 bit and 10 bit coded representation is used and decimal values of the quantized signals are:

– for gamma-corrected R, G, B signals:

$$D'_R = \text{int}\left[\left(219\, E'_R + 16\right) \cdot 2^{n-8}\right]; \tag{2.12}$$

$$D'_G = \text{int}\left[\left(219\, E'_G + 16\right) \cdot 2^{n-8}\right] \tag{2.13}$$

$$D'_B = \text{int}\left[\left(219\, E'_B + 16\right) \cdot 2^{n-8}\right] \tag{2.14}$$

– for luminance and colour difference signals:

$$D'_Y = \text{int}\left[\left(219\, E'_Y + 16\right) \cdot 2^{n-8}\right] \tag{2.15}$$

$$D'_{CR} = \text{int}\left[\left(224\, E'_{CR} + 128\right) \cdot 2^{n-8}\right] \tag{2.16}$$

$$D'_{CB} = \text{int}\left[\left(224\, E'_{CB} + 128\right) \cdot 2^{n-8}\right] \tag{2.17}$$

where n denotes the number of the bit length of the quantized signal.

Derivation of luminance and colour-difference signals via quantized R, G, B signals is realised using equations:

$$D'_Y = \text{int}\left[0.2126\, D'_R + 0.7152\, D'_G + 0.0722\, D'_B\right] \tag{2.18}$$

$$D'_{CR} = \text{int}\left[\left(\frac{0.7874}{1.5748} D'_R - \frac{0.7152}{1.5748} D'_G - \frac{0.0722}{1.5748} D'_B\right) \cdot \frac{224}{219} + 2^{n-1}\right] \tag{2.19}$$

$$D'_{CB} = \text{int}\left[\left(-\frac{0.2126}{1.8556} D'_R - \frac{0.7152}{1.8556} D'_G + \frac{0.9278}{1.8556} D'_B\right) \cdot \frac{224}{219} + 2^{n-1}\right] \tag{2.20}$$

2.4 Colorimetric characteristics of ultra-high definition digital television systems

Colorimetric characteristics of ultra-high definition digital television systems are presented in Table 2.2. In Recommendation ITU-R BT.2020-1 [2.8] a newly proposed signal format for UHDTV systems is specified. For UHDTV systems 10 bit and 12 bit coded representation is used and equations decimal values of the quantized signals are the same for HDTV systems.

TABLE 2.2

Colorimetric characteristics of ultra-high definition digital television systems

<table>
<tr><th>System</th><th>Primaries and reference white chromaticity coordinates</th><th>Opto-electronic and electro–optic conversion characteristics</th><th>Coding equation</th></tr>
<tr>
<td>UHDTV</td>
<td>
<table>
<tr><th></th><th>x</th><th>y</th></tr>
<tr><td>Red</td><td>0.708</td><td>0.292</td></tr>
<tr><td>Green</td><td>0.170</td><td>0.797</td></tr>
<tr><td>Blue</td><td>0.131</td><td>0.046</td></tr>
<tr><td>White D_{65}</td><td>0.3127</td><td>0.3290</td></tr>
</table>
</td>
<td>Opto-electronic conversion:
$E' = \begin{cases} \alpha L^{0,45} - (\alpha - 1) & \text{for} \quad \beta \le E \le 1 \\ 4.5E & \text{for} \quad 0 \le E < \beta \end{cases}$
where E is voltage normalized by the reference white level and proportional to the implicit light intensity that would be detected with a reference camera colour channel R, G, B;
E' is the resulting non-linear signal.
α = 1.099 and β = 0.018 for 10-bit system
α = 1.0993 and β = 0.0181 for 12-bit system</td>
<td>Constant luminance $Y'_C C'_{BC} C'_{RC}$:
$Y'_C = (0.2627\,R + 0.6780\,G + 0.0593\,B)'$
$C'_{BC} = \begin{cases} \dfrac{B' - Y'_C}{1.9404} & \text{for} \quad -0.9702 \le B' - Y'_C \le 0 \\ \dfrac{B' - Y'_C}{1.5916} & \text{for} \quad 0 < B' - Y' \le 0,7908 \end{cases}$
$C'_{RC} = \begin{cases} \dfrac{R' - Y'_C}{1.7184} & \text{for} \quad -0.8592 \le B' - Y'_C \le 0 \\ \dfrac{R' - Y'_C}{0.9936} & \text{for} \quad 0 < B' - Y' \le 0,4968 \end{cases}$
Non-constant luminance $Y'C'_B C'_R$:
$Y' = 0.2627R' + 0.6780G' + 0.0593B'$
$C'_B = \dfrac{B' - Y'}{1.8814}$
$C'_R = \dfrac{R' - Y'}{1.4746}$</td>
</tr>
</table>

2.5 Multimedia systems colorimetric characteristics

Opto-electronic and electro-optic conversions and multimedia systems colorimetric characteristics specified in IEC 61966-2-1 [2.3], IEC 61966-2-2 [2.10], IEC 61966-2-4 [2.11], and IEC 61966-2-5 [2.12], are shown in Table 2.3.

2.6 Colorimetric characteristics of new video applications: Digital cinema systems and LSDI systems

The technological progress has led to the possibility of practical implementation of a new level of video applications, namely, the systems of production and reproduction of scenes with a number of pixels close to 2000×4000 (4k) and 4000×8000 (8k), such as digital cinema (DC) systems [2.13-2.15], LSDI system ACES [2.16] (which can be used for different applications as well as digital cinema) that are by their functionality close to UHDTV systems [2.8].

Among digital cinema systems there are two levels of systems standardized in the world:

– DC systems, characteristics of which were specified by version 1.0 of DCI specification [2.14], which was replaced by DCI specification version 1.2 [2.15];

– DC systems, characteristics of which are specified in the SMPTE 2048-1.

In *DCI specification* [2.14] the use of CIE-31 tristimulus values *X*,*Y*,*Z* as primary colour source digital cinema signals is specified. At the output of the scene capturing system the colour capturing signals *X*,*Y*,*Z* that directly characterize tristimulus values are provided.

A more recent version of the standard for digital cinema system specifies the colour gamut that covers the entire chromaticity diagram and thus provides the possibility of free choice of reproducible colour gamut for reproduction system (*FS-Gamut*) but this feature is somewhat limited in use relative to the first version of digital cinema. Source colour primary signals used in this system are not the CIE-31 tristimulus values *X*,*Y*,*Z* and therefore there is a limited colour gamut with increasing luminance.

SMPTE ST.2048-1 [2.13] defines 4k and 8k image formats primarily for DC content acquisition and creation. These image formats may also be used for acquisition and creation of high quality content for other DC applications. This standard specifies formats compatible with ITU-R BT.709-6 HDTV formats and formats defined with tristimulus values and reference white of Free Scale-Gamut (*FS-Gamut*), colour primary signals transmission *Free Scale-Log* (*FS-Log)* curve and VANC (Vertical Ancillary Code) packet, which conveys the parameter values of user-defined colour space and Log curve.

Default chromaticity coordinates of the primaries and reference white for *FS-Gamut* systems are defined in the standard in compliance with Table 2.4.

SMPTE ST.2065-2 [2.16] specifies the Academy Colour Encoding Specification (ACES) which defines a digital colour image encoding appropriate for both photographed and computer-generated images.

The colour space type shall be colorimetric: additive RGB. The ACES colour space type can also be considered to be of the type input-device-dependent and as such has an associated reference image capture device (RICD). The RGB primaries chromaticity values shall be those found in Table 2.6.

TABLE 2.3

Multimedia systems colorimetric characteristics

<table>
<tr><th>Colour space</th><th>Primaries and reference white chromaticity coordinates</th><th>Opto-electronic and electro-optic conversion characteristics</th><th>Coding equation</th></tr>
<tr>
<td>sRGB
IEC 61966-2-1
Annex F [2.9]</td>
<td><table>
<tr><th></th><th>x</th><th>y</th></tr>
<tr><td>Red</td><td>0.640</td><td>0.330</td></tr>
<tr><td>Green</td><td>0.300</td><td>0.600</td></tr>
<tr><td>Blue</td><td>0.150</td><td>0.060</td></tr>
<tr><td>White D65</td><td>0.3127</td><td>0.3290</td></tr>
</table></td>
<td><u>Opto-electronic conversion</u>:
$E' = 1.055 \cdot L^{1/2.4} - 0.055 \quad \text{for} \quad 0.0031308 \le L \le 1$
$E' = 12.92 \cdot L \quad \text{for} \quad 0 \le L \le 0.0031308$
where $L = R_{\text{sRGB}}, G_{\text{sRGB}}, B_{\text{sRGB}}$ – tristimulus values of sRGB colour space
$E' = R'_{\text{sRGB}}, G'_{\text{sRGB}}, B'_{\text{sRGB}}$ – colour primary coordinates of sR′G′B′ signal space
<u>Electro–optic conversion</u>:
$L = \left[\left(E' + 0.055 \right) / 1.055 \right]^{2.4} \quad \text{for} \quad 0.040449936 \le E' \le 1$
$L = E' / 12.92 \quad \text{for} \quad 0 \le E' < 0.040449936$
<u>Quantized signal representation</u>:
8-bit representation:
$D_{E'(8)} = \text{round}\left(255 \cdot E' \right)$
where $D_{E'(8)} = D_{R'(8)}, D_{G'(8)}, D_{B'(8)}$</td>
<td>sYCC :
$Y'_{\text{sYCC}} = 0.299 R'_{\text{sRGB}} + 0.587 G'_{\text{sRGB}} + 0.114 B'_{\text{sRGB}}$
$C'_{R'\,\text{sYCC}} = \left(R'_{\text{sRGB}} - Y'_{\text{sYCC}} \right) / 1.402$
$C'_{B'\,\text{sYCC}} = \left(B'_{sRGB} - Y'_{\text{sYCC}} \right) / 1.772$
<u>Quantized signal representation</u>:
n-bit representation:
$D_{Y'\text{sYCC}(8)} = \text{round}\left(\left(2^n - 1 \right) \cdot Y'_{\text{sYCC}} \right)$
$D_{C'_R\,\text{sYCC}(8)} = \text{round}\left[\left(\left(2^n - 1 \right) \cdot C'_{R\text{sYCC}} \right) + 2^{n-1} \right]$
$D_{C'_B\,\text{sYCC}(8)} = \text{round}\left[\left(\left(2^n - 1 \right) \cdot C'_{B\text{sYCC}} \right) + 2^{n-1} \right]$</td>
</tr>
<tr>
<td>bg-sRGB
IEC 61966-2-1
Annex G [2.9]</td>
<td><table>
<tr><th></th><th>x</th><th>y</th></tr>
<tr><td>Red</td><td>0.640</td><td>0.330</td></tr>
<tr><td>Green</td><td>0.300</td><td>0.600</td></tr>
<tr><td>Blue</td><td>0.150</td><td>0.060</td></tr>
<tr><td>White D65</td><td>0.3127</td><td>0.3290</td></tr>
</table></td>
<td><u>Opto-electronic conversion</u>:
$E' = \begin{cases} -1.055 \cdot \lvert L \rvert^{1/2.4} + 0.055 & \text{for} \quad -0.53 < L < -0.0031308 \\ 12.92 \cdot L & \text{for} \quad -0.0031308 \lvert < L \rvert < 0.0031308 \\ 1.055 \cdot L^{1/2.4} - 0.055 & \text{for} \quad 0.0031308 < L < 1.68 \end{cases}$
where $L = R_{\text{sRGB}}, G_{\text{sRGB}}, B_{\text{sRGB}}$ – tristimulus values
of sRGB colour space
$E' = R'_{\text{sRGB}}, G'_{\text{sRGB}}, B'_{\text{sRGB}}$ – colour primary coordinates
of sR′G′B′ signal space</td>
<td>bg-sYCC :
$Y'_{\text{sYCC}} = 0.299 R'_{\text{sRGB}} + 0.587 G'_{\text{sRGB}} + 0.114 B'_{\text{sRGB}}$
$C'_{R\,\text{sYCC}} = \left(R'_{\text{sRGB}} - Y'_{\text{sYCC}} \right) / 1.402$
$C'_{B\,\text{sYCC}} = \left(B'_{\text{sRGB}} - Y'_{\text{sYCC}} \right) / 1.772$</td>
</tr>
</table>

TABLE 2.3 (*continued*)

Colour space	Primaries and reference white chromaticity coordinates	Opto-electronic and electro-optic conversion characteristics	Coding equation
		<u>Electro-optic conversion</u>: $L = \begin{cases} \left[-(E'-0.055)/1.055\right]^{2.4} & \text{for } -0,75 < E' < -0.040449936 \\ E'/12.92 & \text{for } -0.040449936 < \lvert E' \rvert < 0.040449936 \\ \left[(E'+0.055)/1.055\right]^{2.4} & \text{for } 0.040449936 < E' < 1,25 \end{cases}$ <u>Quantized signal representation:</u> 16-bit representation: $D_{C'\text{ bg-sRGB}(n)} = \text{round}\left[E'_{\text{sRGB}}\left(255\cdot 2^{n-9}\right)+\left(3\cdot 2^{n-3}\right)\right]$ where $D_{C'\text{ bg-sRGB}(n)} = D_{R'\text{ bg-sRGB}(n)}, D_{G'\text{ bg-sRGB}(n)}, D_{B'\text{ bg-sRGB}(n)}$ Bit depth equals 10, 12 or 16	<u>Quantized signal representation:</u> $D_{Y'\text{bg-sYCC}(n)} = \text{round}\left(\left(2^n-1\right)\cdot Y'_{\text{sYCC}}\right)$ $D_{C'_R\text{bg-sYCC}(n)} = \text{round}\left[\left(\frac{\left(2^n-1\right)\cdot C'_{R\text{sYCC}}}{2}\right)+2^{n-1}\right]$ $D_{C'_B\text{bg-sYCC}(n)} = \text{round}\left[\left(\frac{\left(2^n-1\right)\cdot C'_{B\text{sYCC}}}{2}\right)+2^{n-1}\right]$
scRGB IEC 61966-2-2 [2.10]	<table><tr><td></td><td>*x*</td><td>*y*</td></tr><tr><td>Red</td><td>0.640</td><td>0.330</td></tr><tr><td>Green</td><td>0.300</td><td>0.600</td></tr><tr><td>Blue</td><td>0.150</td><td>0.060</td></tr><tr><td>White D65</td><td>0.3127</td><td>0.3290</td></tr></table>	<u>Opto-electronic conversion</u>: $E' = 1.099\cdot L^{0.45} - 0.099$ for $0.018 \le L \le 1,5$ $E' = 4.5\cdot L$ for $-0.018 \le L \le 0.018$ $E' = -1.099\cdot \lvert L \rvert^{0.45} + 0.099$ for $-0.5 \le L \le 0.018$ where $L = R_{\text{scRGB}}, G_{\text{scRGB}}, B_{\text{scRGB}}$ – tristimulus values of sRGB colour space $E' = R'_{\text{scRGB}}, G'_{\text{scRGB}}, B'_{\text{scRGB}}$ – colour primary coordinates of sR′G′B′ signal space <u>Electro–optic conversion</u>: $L = \begin{cases} \left[-(E'-0.099)/1.099\right]^{2.2} & \text{for } -0,7 < E' < -0.081 \\ E'/4.5 & \text{for } -0.081 < \lvert E' \rvert < 0.081 \\ \left[(E'+0.099)/1.099\right]^{2.2} & \text{for } 0.081 < E' < 1,22 \end{cases}$ scRGB-nl <u>Quantized signal representation:</u> 16-bit representation: $D_{E'nl(16)} = \text{round}\left(8192\cdot E' + 4096\right)$	**scYCC**: $Y'_{\text{scYCC}} = 0.299R'_{\text{scRGB}} + 0.587G'_{\text{scRGB}} + 0.114B'_{\text{scRGB}}$ $C'_{\text{R scYCC}} = \left(R'_{\text{scRGB}} - Y'_{\text{scYCC}}\right)/1.402$ $C'_{\text{B scYCC}} = \left(B'_{\text{scRGB}} - Y'_{\text{scYCC}}\right)/1.772$ <u>Quantized signal representation</u>: 12-bit representation: $D_{Y'\text{sYCC(8bit)}} = \text{round}\left(1280\cdot Y'_{\text{sYCC}} + 1024\right)$ $D_{C'_R\text{ sYCC(12)}} = \text{round}\left[\left(1280\cdot C'_{R\text{sYCC}}\right)+2048\right]$ $D_{C'_B\text{ sYCC(12)}} = \text{round}\left[\left(1280\cdot C'_{B\text{sYCC}}\right)+2028\right]$

TABLE 2.3 (*continued*)

<table>
<tr><th>Colour space</th><th>Primaries and reference white chromaticity coordinates</th><th>Opto-electronic and electro-optic conversion characteristics</th><th>Coding equation</th></tr>
<tr><td></td><td></td><td>

scRGB-nl

Quantized signal representation:

16-bit representation:

$D_{E'nl(16)} = \text{round}\left(8192 \cdot E' + 4096\right)$

where

$D_{E'\text{nl}(16)} = D_{R'\text{nl}(16)}, D_{G'\text{nl}(16)}, D_{B'\text{nl}(16)} =$

$= D_{R'\text{scRGB-nl}(16)}, D_{G'\text{scRGB-nl}(16)}, D_{B'\text{scRGB-nl}(16)}$

12-bit representation:

$D_{E'nl(12)} = \text{round}\left(1280 \cdot E' + 1024\right)$

where

$D_{E'\text{nl}(12)} = D_{R'\text{nl}(12)}, D_{G'\text{nl}(12)}, D_{B'\text{nl}(12)} =$

$= D_{R'\text{scRGB-nl}(12)}, D_{G'\text{scRGB-nl}(12)}, D_{B'\text{scRGB-nl}(12)}$

</td><td>

Quantization relationships using scRGB

<table>
<tr><th>scRGB(16)</th><th>scRGB</th><th>scR′G′B′</th><th>scRGB-nl</th></tr>
<tr><td>N/A</td><td>–0.6038</td><td>–0.8.000</td><td>0</td></tr>
<tr><td>0</td><td>–0.5</td><td>–0.7354</td><td>83</td></tr>
<tr><td>2048</td><td>–0.25</td><td>–0.5371</td><td>337</td></tr>
<tr><td>4096</td><td>0</td><td>0.0000</td><td>1024</td></tr>
<tr><td>12288</td><td>1</td><td>1.0000</td><td>2304</td></tr>
<tr><td>20480</td><td>2</td><td>1.3533</td><td>2756</td></tr>
<tr><td>28672</td><td>3</td><td>1.6125</td><td>3088</td></tr>
<tr><td>36864</td><td>4</td><td>1.8248</td><td>3360</td></tr>
<tr><td>45056</td><td>5</td><td>2.0080</td><td>3594</td></tr>
<tr><td>53248</td><td>6</td><td>2.1708</td><td>3803</td></tr>
<tr><td>61440</td><td>7</td><td>2.3184</td><td>3992</td></tr>
<tr><td>65535</td><td>7.4999</td><td>2.3876</td><td>4080</td></tr>
<tr><td>N/A</td><td>7.5</td><td>2.3877</td><td>4080</td></tr>
<tr><td>N/A</td><td>7.5913</td><td>2.4000</td><td>4096</td></tr>
</table>

</td></tr>
<tr><td>xvYCC
IEC 61966-2-4 [2.11]</td><td>

<table>
<tr><th></th><th>x</th><th>y</th></tr>
<tr><td>Red</td><td>0.640</td><td>0.330</td></tr>
<tr><td>Green</td><td>0.300</td><td>0.600</td></tr>
<tr><td>Blue</td><td>0.150</td><td>0.060</td></tr>
<tr><td>White D65</td><td>0.3127</td><td>0.3290</td></tr>
</table>

</td><td>

Opto-electronic conversion:

$E' = -1.099 \cdot \left|L\right|^{0.45} + 0.099 \quad \text{for} \quad L \le -0.018$

$E' = 4.5 \cdot L \quad \text{for} \quad -0.018 \le L \le 0.018$

$E' = 1.099 \cdot L^{0.45} - 0.099 \quad \text{for} \quad L \ge 0.018$

where

$L = R_{\text{sRGB}}, G_{\text{sRGB}}, B_{\text{sRGB}}$ – tristimulus values of sRGB colour space

$E' = R'_{\text{sRGB}}, G'_{\text{sRGB}}, B'_{\text{sRGB}}$ – colour primary coordinates of sR′G′B′ signal space

Electro-optic conversion:

$$L = \begin{cases} \left[-\left(E' - 0.099\right)/1.099\right]^{2.2} & \text{for} \quad E' < -0.081 \\ E'/4.5 & \text{for} \quad -0.081 < \left|E'\right| < 0.081 \\ \left[\left(E' + 0.099\right)/1.099\right]^{2.2} & \text{for} \quad 0.081 < E' \end{cases}$$

</td><td>

sYCC$_{601}$:

$Y'_{601} = 0.299R'_{sRGB} + 0.587G'_{sRGB} + 0.114B'_{sRGB}$

$C'_{R\,601} = \left(R'_{sRGB} - Y'_{sYCC}\right)/1.402$

$C'_{B\,601} = \left(B'_{sRGB} - Y'_{sYCC}\right)/1.772$

sYCC$_{709}$:

$Y'_{709} = 0.2126R'_{sRGB} + 0.7152G'_{sRGB} + 0.0722B'_{sRGB}$

$C'_{R\,709} = \left(R'_{sRGB} - Y'_{sYCC}\right)/1.5748$

$C'_{B\,709} = \left(B'_{sRGB} - Y'_{sYCC}\right)/1.8556$

</td></tr>
</table>

TABLE 2.3 (*end*)

<table>
<tr><th>Colour space</th><th>Primaries and reference white chromaticity coordinates</th><th>Opto-electronic and electro-optic conversion characteristics</th><th>Coding equation</th></tr>
<tr><td></td><td></td><td></td><td>Quantized signal representation:
n-bit representation is specified:
$Y_{xvYCC(n)} = \text{round}\left[\left(219 \cdot Y' + 16\right) 2^{n-8}\right]$
$D_{C'_R\, xvYCC(n)} = \text{round}\left[\left(224 \cdot C'_R + 128\right) 2^{n-8}\right]$
$D_{C'_B\, xvYCC(n)} = \text{round}\left[\left(224 \cdot C'_B + 128\right) 2^{n-8}\right]$
Y', C'_R, C'_B must be limited as follows:
$Y' \in \overline{-15/219; 238/219}$
$C'_R, C'_B \in \overline{-15/224; 238/224}$</td></tr>
<tr><td>opYCC
IEC 61966-2-5 [2.12]</td><td>

	x	y
Red	0.640	0.330
Green	0.210	0.710
Blue	0.150	0.060
White D65	0.3127	0.3290

</td><td>Opto-electronic conversion:
$E' = L^{0.45}$
where $L = R_{\text{opRGB}}, G_{\text{opRGB}}, B_{\text{opRGB}}$ – tristimulus values of opRGB colour space
$E' = R'_{\text{opRGB}}, G'_{\text{opRGB}}, B'_{\text{opRGB}}$ – colour primary coordinates of opR′G′B′ signal space
Electro-optic conversion:
$L = \left(E'\right)^{2.2}$
Quantized signal representation:
n-bit representation:
$D_{E'\text{op}(n)} = \text{round}\left[\left(2^n - 1\right) E'\right]$
where
$D_{E'\text{op}(n)} = D_{R'\text{op}(n)}, D_{G'\text{op}(n)}, D_{B'\text{op}(n)} =$
$= D_{R'\text{opRGB}(n)}, D_{G'\text{opRGB}(n)}, D_{B'\text{opRGB}(n)}$</td><td>$Y'_{\text{opRGB}} = 0.299 R'_{\text{opRGB}} + 0.587 G'_{\text{opRGB}} + 0.114 B'_{\text{opRGB}}$
$C'_{R'\,\text{opRGB}} = \left(R'_{\text{opRGB}} - Y'_{\text{opRGB}}\right) / 1.402$
$C'_{B'\,\text{opRGB}} = \left(B'_{\text{opRGB}} - Y'_{\text{opRGB}}\right) / 1.772$
Quantized signal representation:
n-bit representation is specified:
$Y_{\text{opRGB}(n)} = \text{round}\left[\left(2^n - 1\right) \cdot Y'_{\text{opRGB}(n)}\right]$
$D_{C'_R\,\text{opRGB}(n)} = \text{round}\left[\left(2^n - 1\right) \cdot C'_{R\,\text{opRGB}(n)} + 2^{n-1}\right]$
$D_{C'_B\, xvYCC(n)} = \text{round}\left[\left(2^n - 1\right) \cdot C'_{B\,\text{opRGB}(n)} + 2^{n-1}\right]$</td></tr>
</table>

TABLE 2.4

Specified chromaticity coordinates of DCDM and ACES systems

	Primaries and reference white	Chromaticity	
		x	***y***
DC (FS-Gamut)	R (R_{FS})	0.73470	0.26530
	G (G_{FS})	0.14000	0.86000
	B (B_{FS})	0.10000	−0.02985
	W	0.31272	0.32903
ACES	R	0.73470	0.26530
	G	0.00000	1.00000
	B	0.00010	−0.07700
	W	0.32168	0.33767

2.7 Colorimetric characteristics of new video applications: Video production systems in multimedia environment

From the point of view of colorimetric characteristics, an important characteristic of the new image applications, including digital graphics systems, digital photography, etc., used for video production, is colour gamut. Graphical information from such image systems as Adobe [2.17] and Eastman Kodak [2.18–2.21] with an extended range of colours, in particular, can be used as sources of video in HDTV and UHDTV programme production, in accordance with Recommendations ITU-R BT.709-6 [2.5] and ITU-R BT.2020-1 [2.8].

In the Adobe system with an extended range of colours, and in Eastman Kodak system, the use of primary colours coordinates different from those in the TV systems, is provided. Tristimulus values of the primaries and reference white of RIMM-ROMM (Kodak), ROM (Kodak) and Wide Gamut (Adobe) systems are presented in Table 2.5.

TABLE 2.5

Chromaticity coordinates of primaries and colour gamut of Kodak and Adobe multimedia systems

System	***R***		***G***		***B***	
	x	***y***	***x***	***y***	***x***	***y***
RIMM-ROMM	0.7347	0.2653	0.1596	0.8404	0.0366	0.0001
ROM	0.8730	0.1440	0.1750	0.9270	0.0850	0.0001
Wide Gamut	0.7347	0.2653	0.1152	0.8264	0.1566	0.0177

In this systems all or part of colour primaries are unreal, and on the basis of this the colour gamut covers almost whole area of chromaticity diagram.

2.8 Characteristics of colorimetry systems for digital video coding systems

Digital video coding system colorimetric characteristics specified in MPEG-2 Video [2.22]; MPEG-4 Visual [2.23]; MPEG-4/AVC [2.24]; MPEG-H HEVC [2.25] are shown in the Tables 2.8, 2.9, 2.10, which combine according data from Tables 6-7, 6-8, 6-9 from MPEG-2 Video, Tables 6-8, 6-9, 6-10 from MPEG-4 Visual, Tables E-8, E-9, E-10 from MPEG-4/AVC and Tables E-3, E-4, E-5 from MPEG-H HEVC.

Primaries chromaticity and reference white coordinates for given parameter values of colour_primaries are shown in Table 2.6.

Opto-electronic conversion characteristics – transfer primaries channel characteristics for given parameter values of transfer_characteristics are shown in Table 2.7. The Table specifies:

L – image primaries tristimulus values, that are relative luminance levels, R,G,B image components

V – relative levels of gamma-corrected signals R,G,B – image components (E'_R, E'_G, E'_B)

E'_Y – normalized luminance signal normalized to $\overline{0;1}$

E'_{PR}, E'_{PB} – colour-difference signals normalized to $\overline{-0.5;+0.5}$.

Luminance signals and colour-difference signals matrixes coefficients for given parameter values of matrix_coefficients are shown in Table 2.8 with exception of cases when matrix_coefficients values are equal to 0 and 8. Value 8 in MPEG-2 Video, MPEG-4/AVC and MPEG-H HEVC corresponds to signal coding Y, C_R, C_B processed by algorithms specified in these standards where C_R, C_B signals are in terms of C_G, C_O. Value 0 in IEC 61966-2-2, MPEG-4/AVC and MPEG-H HEVC corresponds to RGB space signals E'_R, E'_G, E'_B coding processed by algorithms specified in these standards.

TABLE 2.6

Colour primaries for digital video coding in MPEG-2 Video, MPEG-4 Visual, MPEG-4/AVC, and MPEG-H HEVC

<table>
<tr><th>colour_primaries</th><th>Systems and standards</th><th>Primaries and reference white chromaticity coordinates</th></tr>
<tr><td>0</td><td>Forbidden (only MPEG-2 Video and MPEG-4 Visual)
Reserved (only MPEG-4/AVC)</td><td>For future use ITU-T/ISO/IEC</td></tr>
<tr><td>1</td><td>Recommendation ITU-R BT.709-6 [2.5]
IEC 61966-2-1 [2.9] (sRGB or sYCC) (only MPEG-4/AVC and MPEG-H HEVC)
IEC 61966-2-4 [2.11]
SMPTE RP 177 [2.1] (1993) Annex B</td><td><table>
<tr><th></th><th>x</th><th>y</th></tr>
<tr><td>Red</td><td>0.640</td><td>0.330</td></tr>
<tr><td>Green</td><td>0.300</td><td>0.600</td></tr>
<tr><td>Blue</td><td>0.150</td><td>0.060</td></tr>
<tr><td>White D_{65}</td><td>0.3127</td><td>0.3290</td></tr>
</table></td></tr>
<tr><td>2</td><td>Unspecified</td><td>Image characteristics are unknown or are determined by the application</td></tr>
<tr><td>3</td><td>Reserved</td><td>For future use by ITU-T/ISO/IEC</td></tr>
<tr><td>4</td><td>Recommendation ITU-R BT.470-6 system M
NTSC 1953 Recommendation for transmission standards for colour television
US FCC Title 47 Code of Federal Regulations (2004) 73.682 (a) (20)</td><td><table>
<tr><th></th><th>x</th><th>y</th></tr>
<tr><td>Red</td><td>0.67</td><td>0.33</td></tr>
<tr><td>Green</td><td>0.21</td><td>0.71</td></tr>
<tr><td>Blue</td><td>0.14</td><td>0.08</td></tr>
<tr><td>White C</td><td>0.310</td><td>0.316</td></tr>
</table></td></tr>
<tr><td>5</td><td>Recommendation ITU-R BT.1700 [2.3] 625 PAL or 625 SECAM
Recommendation ITU-R BT.601 [2.4] 625
Recommendation ITU-R BT.470-6 systems B, G</td><td><table>
<tr><th></th><th>x</th><th>y</th></tr>
<tr><td>Red</td><td>0.64</td><td>0.33</td></tr>
<tr><td>Green</td><td>0.29</td><td>0.60</td></tr>
<tr><td>Blue</td><td>0.15</td><td>0.06</td></tr>
<tr><td>White D_{65}</td><td>0.3127</td><td>0.3290</td></tr>
</table></td></tr>
<tr><td>6</td><td>Recommendation ITU-R BT.1700 [2.3] NTSC
SMPTE 170M [2.2]
Recommendation ITU-R BT.601 [2.4] 525</td><td><table>
<tr><th></th><th>x</th><th>y</th></tr>
<tr><td>Red</td><td>0.630</td><td>0.340</td></tr>
<tr><td>Green</td><td>0.310</td><td>0.595</td></tr>
<tr><td>Blue</td><td>0.155</td><td>0.070</td></tr>
<tr><td>White D_{65}</td><td>0.3127</td><td>0.3290</td></tr>
</table></td></tr>
</table>

TABLE 2.6 (*end*)

<table>
<tr><th>colour_primaries</th><th>Systems and standards</th><th>Primaries and reference white chromaticity coordinates</th></tr>
<tr><td>7</td><td>SMPTE 240M [2.26]</td><td><table><tr><td></td><td>x</td><td>y</td></tr><tr><td>Red</td><td>0.630</td><td>0.340</td></tr><tr><td>Green</td><td>0.310</td><td>0.595</td></tr><tr><td>Blue</td><td>0.155</td><td>0.070</td></tr><tr><td>White D_{65}</td><td>0.3127</td><td>0.3290</td></tr></table></td></tr>
<tr><td rowspan="2">8</td><td>Reserved (MPEG-2 Video)</td><td>For future use by ITU-T | ISO/IEC</td></tr>
<tr><td>Generic film (colour filters using standard illuminant C)
(only MPEG-4 Video, MPEG-4/AVC, and MPEG-H HEVC)</td><td><table><tr><td></td><td>x</td><td>y</td><td></td></tr><tr><td>Red</td><td>0.681</td><td>0.319</td><td>(Wratten 25)</td></tr><tr><td>Green</td><td>0.243</td><td>0.692</td><td>(Wratten 58)</td></tr><tr><td>Blue</td><td>0.145</td><td>0.049</td><td>(Wratten 47)</td></tr><tr><td>White C</td><td>0.310</td><td>0.316</td><td></td></tr></table></td></tr>
<tr><td rowspan="2">9</td><td>Reserved (only MPEG-2 Video and MPEG-4 Visual)</td><td>For future use by ITU-T | ISO/IEC</td></tr>
<tr><td>Rec. ITU-R BT.2020 [2.8] (only MPEG-4/AVC and MPEG-H HEVC)</td><td><table><tr><td></td><td>x</td><td>y</td></tr><tr><td>Red</td><td>0.708</td><td>0.292</td></tr><tr><td>Green</td><td>0.170</td><td>0.797</td></tr><tr><td>Blue</td><td>0.131</td><td>0.046</td></tr><tr><td>White D_{65}</td><td>0.3127</td><td>0.3290</td></tr></table></td></tr>
<tr><td rowspan="2">10</td><td>Reserved (only MPEG-2 Video and MPEG-4 Visual and MPEG-4 AVC)</td><td rowspan="2">For future use by ITU-T | ISO/IEC
<table><tr><td></td><td>x</td><td>y</td></tr><tr><td>X</td><td>1</td><td>0</td></tr><tr><td>Y</td><td>0</td><td>1</td></tr><tr><td>Z</td><td>0</td><td>0</td></tr><tr><td>White</td><td>1/3</td><td>1/3</td></tr></table></td></tr>
<tr><td>SMPTE ST 428-1 CIE 1931 XYZ (only MPEG-H HEVC)</td></tr>
<tr><td>11-255</td><td>Reserved</td><td>For future use by ISO/IEC</td></tr>
</table>

TABLE 2.7

Transfer characteristics for digital video coding in MPEG-2 Video, MPEG-4 Visual, MPEG-4/AVC, and MPEG HEVC

transfer_characteristic	**Systems and standards**	**Transfer characteristic**
0	Forbidden (*only MPEG-2 Video and MPEG-4 Visual*) Reserved (*only MPEG-4/AVC and MPEG-H HEVC*)	For future use by ITU-T | ISO/IEC
1	Recommendation ITU-R BT.709 [2.5]	$V = 1.099L^{0,45} - 0.099$ for $0.018 \le L \le 1$ $V = 4.500L$ for $0 \le L < 0.018$ where $L = R, G, B$ – colour primaries tristimulus values, $V = R', G', B'$ – colour primaries signals
2	Unspecified	Image characteristics are unknown or are determined by the application
3	Reserved	For future use by ITU-T | ISO/IEC
4	Recommendation ITU-R BT.470-6 system M Recommendation ITU-R BT.1700 [2.3] 625 PAL or 625 SECAM (*only MPEG-4 Visual and MPEG-4/AVC and MPEG-H HEVC*) US NTSC 1953 Recommendation for transmission standards for colour television US FCC Title 47 Code of Federal Regulations (2004) 73.682 (a) (20)	Assumed displayed gamma 2.2
5	Recommendation ITU-R BT.1700 [2.3] 625 PAL or 625 SECAM (*only MPEG-2 Video*) Recommendation ITU-R BT.470-6 systems B, G	Assumed displayed gamma 2.8 *Note*. This value conflicts with Recommendation ITU-R BT.1700 (2007 revision) and accordingly to this Recommendation has to be changed to 2.2
6	Recommendation ITU-R BT.1700 [2.3] NTSC SMPTE 170M [2.2] Recommendation ITU-R BT.601 [2.4] 525 or 625 US NTSC 1953 Recommendation for transmission standards for colour television (*only MPEG-4 Visual and MPEG-4/AVC*)	$V = 1.099L^{0,45} - 0.099$ for $0.018 \le L \le 1$ $V = 4.500L$ for $0 \le L < 0.018$

TABLE 2.7 (*continued*)

transfer_characteristic	Systems and standards	Transfer characteristic
7	SMPTE 240M [2.26]	$V = 1.1115L^{0,45} - 0.1115$ for $0.0228 \le L \le 1$ $V = 4.0L$ for $0 \le L \le 0.0228$
8	Linear transfer characteristic	$V = L$ $V = L$ for $0 \le L < 1$
9	Logarithm transfer characteristic (100:1 range)	$V = 1.0 + \mathrm{Log}_{10}(L)/2$ for $0.01 \le L \le 1$ $V = 0.0$ for $L < 0.01$
10	Logarithm transfer characteristic (316.22777:1 range)	$V = 1.0 + \mathrm{Log}_{10}(L) \div 2.5$ for $0.0031622777 \le L \le 1$ $V = 0.0$ for $L < 0.0031622777$
11	IEC 61966-2-4 [2.11]	$V = 1.099L^{0.45} - 0.099$ for $0.018 \le L$ $V = 4.500L$ for $-0.018 \le L \le 0.018$ $V = -\left[1.099(-L)^{0.45} - 0.099\right]$ for $L \le -0.018$
12	Extended colour gamut system	$V = 1.099L_C^{0.45} - 0.099$ for $0.018 \le L_C < 1.33$ $V = 4.500L_C$ for $-0.0045 \le L_C < 0.018$ $V = -\left[1.099(-4L_C)^{0.45} - 0.099\right]/4$ for $-0,25 \le L_C < -0.0045$
13	Reserved (*MPEG-2 Video and MPEG-4 Visual*)	For future use by ITU-T | ISO-IEC
	IEC 61966-2-1 (sRGB or sYCC) (*only MPEG-H HEVC*)	$V = 1.055L^{1/2.4} - 0.055$ for $0.0031308 \le L \le 1$ $V = 12.92L$ for $0 \le L \le 0.0031308$
14	Reserved (*MPEG-2 Video and MPEG-4 Visual*)	For future use by ITU-T | ISO-IEC
	Rec. ITU-R BT.2020 for 10 bit system (*only MPEG-H HEVC*)	$V = 1.099L^{0.45} - 0.099$ for $0.018 \le L \le 1$ $V = 4.5L$ for $0 \le L \le 0.018$
15	Reserved (*MPEG-2 Video and MPEG-4 Visual*)	For future use by ITU-T | ISO-IEC
	Rec. ITU-R BT.2020 for 12 bit system (*only MPEG-H HEVC*)	$V = 1.0993L^{0.45} - 0.0993$ for $0.0181 \le L \le 1$ $V = 4.5L$ for $0 \le L \le 0.0181$

TABLE 2.7 (*end*)

transfer_characteristic	**Systems and standards**	**Transfer characteristic**
16	Reserved (*only MPEG-2 Video and MPEG-4 Visual and MPEG-4/AVC*)	For future use by ITU-T | ISO-IEC
	SMPTE ST 2084 for 10, 12, 14 and 16 bit systems (*only MPEG-H HEVC*)	$V = \left(\left(c_1 + c_2 L_C^n \right) / \left(1 + c_3 L_C^n \right) \right)^m$ for all values of L_C $c_1 = c_3 - c_2 + 1 = 3424/4096 = 0.8359375$ $c_2 = 32 \times 2413/4096 = 18.8515625$ $c_3 = 32 \times 2392/4096 = 18.6875$ $m = 128 \times 2523/4096 = 78.84375$ $n = 0.25 \times 2610/4096 = 0.1593017578125$ for which L_C equal to 1 for peak white is ordinarily intended to correspond to a display luminance level of 10 000 candelas per square metre
17	Reserved (*MPEG-2 Video and MPEG-4 Visual and MPEG-4/AVC*)	For future use by ITU-T | ISO-IEC
	SMPTE ST 428-1 (*only MPEG-H HEVC*)	$V = \left(48 L_C / 52.37 \right)^{(1/2.6)}$ for all values of L_C, for which L_C equal to 1 for peak white is ordinarily intended to correspond to a display luminance level of 48 candelas per square metre
18-255	Reserved	For future use by ITU-T | ISO-IEC

TABLE 2.8

Matrix coefficients for digital video coding in MPEG-2 Video, MPEG-4 Visual, MPEG-4/AVC, and MPEG-H HEVC

matrix_coefficients	Systems and standards	Matrix
0	Forbidden (*MPEG-2 Video, MPEG-4 Visual*) sRGB (IEC 61966-2-1) (MPEG-4/AVC, MPEG-H HEVC)	Typically referred as *RGB*
1	Recommendation ITU-R BT.709 [2.5] IEC 61966-2-1 (sYCC) (*only MPEG-4/AVC and MPEG-H HEVC*) IEC 61966-2-4 $xvYCC_{709}$ [2.11] SMPTE RP 177 Annex B [2.1]	$E'_Y = 0.2126E'_R + 0.7152E'_G + 0.0722E'_B$ $E'_{PR} = (E'_R - E'_Y)/1.5748$ $E'_{PB} = (E'_B - E'_Y)/1.8556$
2	Unspecified	Image characteristics are unknown or determined by the application
3	Reserved	For future use ITU-T | ISO-IEC
4	US NTSC 1953 Recommendation for transmission standards for colour television (*only MPEG-2 Video, MPEG-4 Visual, MPEG HEVC*) US FCC Title 47 Code of Federal Regulations (2004) 73.682 (a) (20) (*only MPEG-4/AVC)* Recommendation ITU-R BT.470-6 system M (*only MPEG-H HEVC*)	$E'_Y = 0.30E'_R + 0.59E'_G + 0.11E'_B$ $E'_{P_R} = (E'_R - E'_Y)/1.40$ $E'_{P_B} = (E'_B - E'_Y)/1.78$
5	Recommendation ITU-R BT.1700 [2.3] 625 PAL and 625 SECAM IEC 61966-2-4 $xvYCC_{601}$ (*MPEG-2 Video, MPEG-4 Visual, MPEG-4/AVC*) Recommendation ITU-R BT.470-6 systems B, G) Recommendation ITU-R BT.601 [2.4] 625	$E'_Y = 0.299E'_R + 0.587E'_G + 0.114E'_B$ $E'_{P_R} = (E'_R - E'_Y)/1.402$ $E'_{P_B} = (E'_B - E'_Y)/1.772$

TABLE 2.8 (*continued*)

matrix_coefficients	Systems and standards	Matrix
6	Recommendation ITU-R BT.1700 [2.3] NTSC SMPTE 170M [2.2] IEC 61966-2-4 xvYCC$_{601}$ [2.11] (*only MPEG-2 Video, MPEG-4 Visual, MPEG-4/AVC*) Recommendation ITU-R BT.601 [2.4]	$E'_Y = 0.299E'_R + 0.587E'_G + 0.114E'_B$ $E'_{P_R} = (E'_R - E'_Y)/1.402$ $E'_{P_B} = (E'_B - E'_Y)/1.772$
7	SMPTE 240M (1999) [2.26]	$E'_Y = 0.212E'_R + 0.701E'_G + 0.087E'_B$ $E'_{PR} = 0.500E'_R - 0.445E'_G - 0.055E'_B$ $E'_{PB} = -0.116E'_R - 0.384E'_G + 0.500E'_B$
8	(*only MPEG-2, MPEG-4/AVC, MPEG-H HEVC*)	*YCgCo* where *Cg* and *Co* may be referred as C_B and C_R respectively, where if video_range is equal to 0 $R = \max\left[0, \min\left[\left(2^n - 1\right), 2^{n-8}\left(219E'_R + 16\right)\right]\right]$ $G = \max\left[0, \min\left[\left(2^n - 1\right), 2^{n-8}\left(219E'_G + 16\right)\right]\right]$ $B = \max\left[0, \min\left[\left(2^n - 1\right), 2^{n-8}\left(219E'_B + 16\right)\right]\right]$ if video_range is equal to 1 $R = \max\left[0, \min\left[\left(2^n - 1\right), \left(2^n - 1\right)E'_R\right]\right]$ $G = \max\left[0, \min\left[\left(2^n - 1\right), \left(2^n - 1\right)E'_G\right]\right]$ $B = \max\left[0, \min\left[\left(2^n - 1\right), \left(2^n - 1\right)E'_B\right]\right]$ for *n* bit video.

TABLE 2.8 (*end*)

matrix_coefficients	Systems and standards	Matrix
		Y, C_B and C_R are related to R, G and B as: $Y = \text{round}\left[0.5G + 0.25(R+B)\right]$ $C_B = \text{round}\left[0.5G - 0.25(R+B)\right] + 2^{n-1}$ $C_R = \text{round}\left[0.5(R-B)\right] + 2^{n-1}$
9	Rec. ITU-R BT.2020 non-constant luminance system	$Y' = 0.2627R' + 0.6780G' + 0.0593B'$ $C'_B = \frac{B'-Y'}{1.8814}$ $C'_R = \frac{R'-Y'}{1.4746}$
10	Rec. ITU-R BT.2020 constant luminance system	$Y'_C = (0.2627\ R + 0.6780\ G + 0.0593\ B)'$ $C'_{BC} = \begin{cases} \frac{B'-Y'_C}{1.9404} & \text{for} \quad -0.9702 \le B'-Y'_C \le 0 \\ \frac{B'-Y'_C}{1.5916} & \text{for} \quad 0 < B'-Y' \le 0,7908 \end{cases}$ $C'_{RC} = \begin{cases} \frac{R'-Y'_C}{1.7184} & \text{for} \quad -0.8592 \le B'-Y'_C \le 0 \\ \frac{R'-Y'_C}{0.9936} & \text{for} \quad 0 < B'-Y' \le 0,4968 \end{cases}$
11-255		Reserved. For future use ITU-T | ISO-IEC

2.9 Colorimetric characteristics of professional and consumer displays

Today CRT and flat panel displays are used for professional and consumer purposes. The requirements to professional and consumer displays characteristics, particularly, colorimetric characteristics, are specified in [2.27–2.30]. Flat panels are displacing CRT displays.

In Recommendation ITU-R BT.1728-1 [2.27] guidance on the use of flat panel displays in television production and postproduction is formulated. In this Recommendation, in the section of *considering*, it is stated that from point of view of colorimetric characteristics:

At the present stage of technology development, flat panel displays present images whose rendition depends on the type of technology used in the flat panel, and often also depends on the display brand and model, even for displays that use the same flat panel technology. Flat panel displays are often adjusted to present images at a higher white colour temperature than the standardized one (D 6500), so that images typically appear “colder”. The image rendition of some flat panel displays depends on the angle under which the display is viewed. The technology of flat panel displays is developing at a fast pace, and one may expect some performance improvements in future flat panel displays.

On the base of these considerations, it is specified that the arbitrary use of any make or model of flat panel display should be avoided in television programme production/ postproduction applications, notably in those applications in which a reliably correct and uniform image rendition is required, such as in control rooms and viewing rooms, where television images are balanced and matched and where programme quality is checked and certified; and in television production rooms and control rooms, image quality should be monitored on either a professional cathode-ray-tube (CRT) studio monitor, if available, or on a professional flat panel display of a brand and model which has been checked in advance to reasonably match the performance of a CRT studio monitor.

In Recommendation ITU-R BT.1886 [2.28] the reference electro-optical transfer function for flat panel displays used in HDTV studio production is specified. It is specified in the recommendation, that with the introduction of new display technologies which have entirely different characteristics to the CRT displays, it is necessary to define the EOTF of new devices that emulate that of the CRT displays. In measuring the EOTF of a large number of CRTs it was determined that the EOTF of the CRT was in fact highly variable when the brightness/contrast was adjusted, it is therefore not possible to 100% emulate CRT capability (or limitations).

Recommendation ITU-R BT.2022 [2.29] provides general viewing conditions for subjective assessment of quality of SDTV and HDTV television pictures on flat panel displays. These conditions reflect viewing conditions in laboratory and home environment on the screen of professional and consumer displays consequently.

Professional monitors seldom use technologies to improve their contrast in a high illuminance environment, so it is possible they do not comply with the requested contrast standard if used in a high illuminance environment.

Consumer monitors typically use technologies to give higher contrast in a high illuminance environment.

We have emissive displays, reflective displays, shuttered illumination displays, etc., they all behave the different way. Today’s consumer displays (excluding special processing) are approaching the point where they can be considered quasi professional displays.

EBU document TECH-3325 [2.30] provides methods of measurement characteristics of professional studio monitors, particularly, such characteristics, related to colorimetry image quality:

– Achievable contrast

– Black level

– Chromaticity of the primary red (R), green (G), and blue (B) light emissions
– Colour gamut
– Colour temperature.

CHAPTER 3

Colour appearance models

3.1 General requirements for colour appearance models

As it was previously stated, the perception of colours plays a major part in overall image quality perception. R.W.G. Hunt in [3.1] has formulated six approaches to colour reproduction. Two of them seem to be suitable for implementation in TV systems:

– Equivalent colour reproduction. In this approach, the goal is achieving equality of chromaticities and absolute and relative luminances of colours of the original scene and reproduced image being viewed under different conditions.

– Preferable colour reproduction. The purpose of this approach is not achievement of strict equality of colour perception of display and standard images, but reproduction of colours in such a way that the colours of the estimated image were more pleasant for an observer, than colours of original scene.

It should be noted that reproduction of colours from memory has a substantial influence on judgments about the reproduced image; but it cannot be used as independent criterion.

Colour spaces are used for the mathematical representation of colours independently of the spectral power distribution of the optical radiation. To take account of viewing conditions (that is necessary for colour transforms and colorimetric distortion correction) various colour appearance models have been developed. The most widely used colour appearance models are CIELUV and CIELAB [3.1, 3.3–3.7].

A description of the CIE models used (i.e. CIELUV and CIELAB) is given in sub-chapters 3.2 and 3.3, and the description of CIECAM02 model [3.2, 3.5] and its modification proposed by Luo and al. [3.8] is given in Annex A.

The results of testing published have shown that predictions obtained by using CIECAM02-based colour spaces best match all available colour appearance data and can be considered to become a base for further research work on development of TV and related video systems, and for the development of colour appearance models for image quality assessment systems, particularly colorimetric quality assessment.

The problems of TV colorimetry, the use of colour appearance models and topics for future studies are pointed out in [3.9].

3.2 CIELUV Model

Input data: X, Y, Z – CIE 1931 tristimulus values of the sample; X_W, Y_W, Z_W – CIE 1931 tristimulus values for reference white.

Stimulus lightness is defined as follows:

$$L^* = \begin{cases} 116\left(Y/Y_W\right)^{1/3} - 16 & \text{for} \quad Y/Y_W > 0.008856 \\ L^* = 903.3\left(Y/Y_W\right) & \text{for} \quad Y/Y_W \le 0.008856 \end{cases} \tag{3.1}$$

Opponent axes:

$$u^* = 13L^*\left(u - u_w\right) \qquad v^* = 19.5L^*\left(v - v_w\right) \tag{3.2}$$

where

$$u = 4X/(X + 15Y + 3Z) \qquad v = 9Y/(X + 15Y + 3Z)$$

Chroma and hue:

$$C^*_{uv} = \left(u^{*2} + v^{*2}\right)^{1/2} \qquad h^*_{uv} = \tan^{-1}\left(v^*/u^*\right) \tag{3.3}$$

3.3 CIELAB Model

Input data: X, Y, Z – CIE 1931 tristimulus values of the sample; X_W, Y_W, Z_W – CIE 1931 tristimulus values for reference white.

The lightness of stimulus is defined as follows:

$$L^* = \begin{cases} 116\left(Y/Y_W\right)^{1/3} - 16 & \text{for} \quad Y/Y_W > 0.008856 \\ 903.3\left(Y/Y_W\right) & \text{for} \quad Y/Y_W \le 0.008856 \end{cases} \tag{3.4}$$

Opponent axes:

$$a^* = 500\left[f\left(X/X_W\right) - f\left(Y/Y_W\right)\right] \qquad b^* = 200\left[f\left(Y/Y_W\right) - f\left(Z/Z_W\right)\right] \tag{3.5}$$

where:

$$f(\varsigma) = \begin{cases} (\varsigma)^{1/3} & \text{for} \quad \varsigma \ge 0.008856 \\ 7.787(\varsigma) + 16/116 & \text{for} \quad \varsigma \le 0.008856 \end{cases}$$

Chroma and hue:

$$C^*_{ab} = \left(a^{*2} + b^{*2}\right)^{1/2} \qquad h^*_{ab} = \tan^{-1}\left(b^*/a^*\right) \tag{3.6}$$

CHAPTER 4

Colour difference estimation

4.1 Introductory notes

Objective estimation of colour reproduction quality can be based on the usage of colour spaces. In such a case, the distance between the points of reference and reproduced colours in colour space can correspond to subjective colour difference. There are two possible ways [4.1, 4.2]:

1 Colour space is perceptually uniform, i.e. in that subjective colour difference corresponds to equal distance between points of colours. In such case, distance between the points of colours is estimated by Euclidian metrics, for example in CIELAB, CIELUV and CIECAM02 models.

2 Colour space is non-uniform. In such case, correction of metric is required, as this was done in the set of equations for estimation colour difference based on CIELAB: CMC, CIE94, CIEDE2000 models.

Distances between points of colours in the colour spaces of CIELUV and CIELAB systems are defined respectively as:

$$\Delta E^*_{uv} = \left(\Delta L^{*2} + \Delta u^{*2} + \Delta v^{*2}\right)^{1/2}; \quad \Delta E^*_{ab} = \left(\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}\right)^{1/2}, \tag{4.1}$$

where ΔL^*, Δa^*, Δb^*, Δu^*, Δv^* conform to arithmetic difference between corresponding coordinates of reference and considered colours.

These metrics are traditional and widely used.

In 2006 a set of colour difference formulae applied to large and small colour difference was tested by Luo et al. [4.3]. CIEDE2000, BFD and CAM02-SCD have shown the best performance for assessment of small (nearly $2,5\ \Delta E^*_{ab}$ units) colour differences among ten formulae tested. The CAM02-UCS and DIN99d [4.4] formulae performed slightly poorer. The metrics performed best for assessing of large (nearly $10\ \Delta E^*_{ab}$ units) colour differences are CAM02-LCD, OSA and GLAB and (with only a slightly poorer performance) CAM02-UCS, which is based on the recently defined colour appearance model CIECAM02 and represents a good compromise for all amounts of colour differences.

CIEDE2000 metric [4.5] is presented in the following sub-chapter 4.2. Other colour difference formulae mentioned above are explained in references [4.1–4.4]. They are not used in broadcasting today but may be used in future.

4.2 CIEDE2000

The metric based on CIELAB colour appearance model (see previous section)

$$\Delta E_{00} = \left\{ \left(\frac{(\Delta L')^2}{k_L S_L}\right) + \left(\frac{(\Delta C'_{ab})^2}{k_C S_C}\right) + \left(\frac{(\Delta H'_{ab})^2}{k_H S_H}\right) + R_T \left(\frac{(\Delta C'_{ab})^2}{k_C S_C}\right)\left(\frac{(\Delta H'_{ab})^2}{k_H S_H}\right) \right\}^{1/2} \tag{4.2}$$

where:

$$L' = L^*; \quad a' = (1+G)a^*; \quad b' = b^*; \quad C'_{ab} = \sqrt{a'^2 + b'^2}; \quad h'_{ab} = \tan^{-1}(b'/a');$$

$$G = 0.5\left[1 - \left(\left(\overline{C^*_{ab}}\right)^7 \Big/ \left(\left(\overline{C^*_{ab}}\right)^7 + 25^7\right)\right)^{1/2}\right]$$

$\overline{C^*_{ab}}$ – arithmetic mean of C^*_{ab} values of twocolor patches being tested;

$$\Delta L' = L'_R - L'_S; \quad \Delta C'_{ab} = C'_{ab,R} - C'_{ab,S}; \quad \Delta H_{ab} = 2\sqrt{C'_{ab,R}C'_{ab,S}}\sin\left(\frac{\Delta h'_{ab}}{2}\right); \quad \Delta h'_{ab} = h'_{ab,R} - h'_{ab,S}$$

$$S_L = 1 + 0.015\left(\overline{L'} - 50\right)^2 \Big/ \left(20 + \left(\overline{L'} - 50\right)^2\right)^{1/2}; \quad S_C = 1 + 0.045\overline{C'_{ab}}; \quad S_H = 1 + 0.015\overline{C'_{ab}}T$$

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

$\overline{L'}$ and $\overline{C'_{ab}}$ – arithmetic mean values of L' and C'_{ab} of two colour patches being tested;

$\overline{h'_{ab}}$ – arithmetic mean values of hue values h_{ab} of colour patches under consideration:

$$\overline{h'_{ab}} = \begin{cases} \overline{h'_{ab}} = \left(h'_{ab,S} + h'_{ab,R}\right)/2 & \text{for} \quad \overline{h'_{ab}} \le 180^\circ \\ \overline{h'_{ab}} = \left(h'_{ab,S} + h'_{ab,R}\right)/2 - 180 & \text{for} \quad \overline{h'_{ab}} > 180^\circ \end{cases}$$

$$R_T = -\sin(2\Delta\theta)R_C; \quad \Delta\theta = 30\exp\left\{-\left[\left(\overline{h'_{ab}} - 275^\circ\right)/25\right]^2\right\}; \quad R_C = 2\left(\left(\overline{C'_{ab}}\right)^7 \Big/ \left[\left(\overline{C'_{ab}}\right)^7 + 25^7\right]\right)^{1/2}$$

The values of k_L, k_C, k_H are set depending on application, default values are 1.

CHAPTER 5

Image appearance and image difference models

5.1 Introductory notes

Colour appearance models account for many changes in viewing conditions, but are mainly focused on changes in the colour of the illumination, the illumination level, and surround relative luminance. Such models do not directly incorporate any of the spatial or temporal properties of human vision and the perception of images. They essentially treat each pixel of an image (and each frame of a video) as completely independent stimuli.

An image appearance model extends colour appearance models to incorporate properties of spatial and temporal vision allowing prediction of appearance in complex stimuli and the measurement of image differences.

In this section some of the image appearance models and their application to image difference assessment (and thus to image quality assessment) are shown.

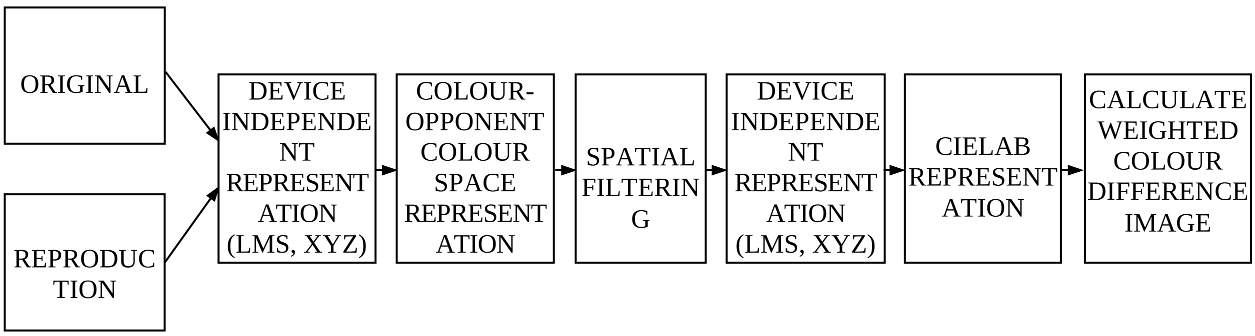
System S-CIELAB is described in the following sub-chapter 5.2. Further systems (iCAM and MOM), are described in Annex B. These may be relevant to television, because they do not only describe colour space but also spatio-temporal image space.

5.2 S-CIELAB

S-CIELAB [5.1] was designed specifically as a spatial extension of the CIELAB colour difference space. The spatial extension is essentially a vision-based pre-processing step based on traditional CIE colorimetry, and can be thought of as a spatial vision enhancement to a colour difference equation. The general flowchart is shown in Fig. 5.1

FIGURE 5.1

Flowchart of S-CIELAB



The model takes two images as an input. The first stage in the calculation is to transform the images into colour-opponent colour space AC_1C_2, representing an achromatic, a red-green and a blue-yellow channels:

$$\begin{bmatrix} A \\ C_1 \\ C_2 \end{bmatrix} = \begin{bmatrix} 0.279 & 0.720 & -0.107 \\ -0.449 & 0.290 & 0.077 \\ 0.086 & 0.590 & -0.501 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

The spatial filters that approximate human CSFs are used to eliminate the information that is imperceptible to the visual system and normalize colour differences at spatial frequencies that are visible. The traditional S-CIELAB model uses two-dimensional separable convolution kernels. These kernels are unit sum kernels, in the form of a series of Gaussian functions. The unit sum was designed such that for large uniform areas S-CIELAB predictions are identical to the corresponding CIELAB predictions. The spatial form of the convolution kernels are the following:

$$\text{filter} = k\sum_i w_i E_i; \qquad E_i = k_i e^{-\left(x^2+y^2\right)/\sigma_i^2}$$

The parameters k and k_i normalize the filters such that they sum to one, thus preserving the mean colour value for uniform areas. The parameters w_i and σ_i represent the weight and the spread (in degrees of visual angle) of the Gaussian functions, respectively.

The separable nature of the kernels allows for the use of two relatively simple 1-D convolutions of the colour planes, rather than a more complex 2-D convolution.

If computationally feasible it might be desirable to perform the spatial filtering in the frequency domain, rather than the spatial domain. The characteristics of luminance and chrominance filters are the following:

TABLE 5.1

Weight and spread of Gaussian convolution kernel

Filter	**Weight(w_i)**	**Spread (σ_i)**
Achromatic (i=1)	1.00327	0.0500
Achromatic (i=2)	0.11442	0.2250
Achromatic (i=3)	−0.11769	7.0000
Red-Green (i=1)	0.61673	0.0685
Red-Green (i=2)	0.38328	0.8260
Blue-Yellow (i=1)	0.56789	0.0920
Blue-Yellow (i=2)	0.43212	0.6451

$$CSF_{lum}\left(f\right) = a\cdot f^{c}\cdot e^{-bf}; \quad CSF_{chrom}\left(f\right) = a_1\cdot e^{-b_1 f^{c_1}} + a_2\cdot e^{-b_2 f^{c_2}}$$

The parameters, a, b, and c can be fit to existing experimental data, if available. Alternatively values of 75, 0.2, and 0.8 for a, b, and c respectively fit reasonably well with the S-CIELAB filters.

TABLE 5.2

Parameters for chrominance CSFs

Parameter	**Red-Green**	**Blue-Yellow**
a1	109.1413	7.0328
b1	−0.0004	0.0000
c1	3.4244	4.2582
a2	93.5971	40.6910
b2	−0.0037	–0.1039
c2	2.1677	1.6487

The filtered opponent channels are then transformed back into CIE *XYZ* space as shown below:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.979 & -1.535 & 0.445 \\ 1.189 & 0.764 & 0.135 \\ 1.232 & 1.163 & 2.079 \end{bmatrix} \begin{bmatrix} A \\ C_1 \\ C_2 \end{bmatrix}$$

The filtered *XYZ* pixel values for both the original and the test image are then transformed into the CIELAB space and the colour differences are determined on pixel-by-pixel basis by using colour difference formulae.

CHAPTER 6

Colour gamuts transmitted and reproduced by television and related systems

In this section, the evaluations of colour gamuts for SDTV, HDTV and UHDTV systems in colour spaces of XYZ and of CAM02-UCS with consideration of TV system parameters and image luminance levels are presented. CAM02-UCS is currently not used in practice in television. However, the presentation of colour gamut in uniform CAM02-UCS space provides possibility to evaluate the effect of variation of viewing conditions on colour gamut.

Presented evaluations are related to possible principles of realization extended colour gamut in accordance with Table 5 of Report ITU-R BT.2246 [6.1] are made. More detailed information is presented in [6.12-6.14].

6.1 Conventional colour gamut and extended colour primaries triangle television systems

The range of the colours reproduced by conventional colour gamut SDTV and HDTV systems [6.2–6.5] and by extended triangle UHDTV systems [6.6] are defined by the range of primaries signals variation limited by zero and unit values:

$$0 \le R, G, B \le 1$$

XYZ colour gamut boundaries on (x, y) plane are presented here for systems with primaries specified in Recommendations ITU-R BT.601-7 [6.2] (SDTV), ITU-R BT.709-6 [6.3], ITU-R BT.1543-1 [6.4] and ITU-R BT.1847-1 [6.5] (HDTV) and in Recommendation ITU-R BT.2020-1 [6.6] (UHDTV).

Transferred colour gamut area in XYZ space and CAM02-UCS space for $Y = 0.1$, $Y = 0.25$ and $Y = 0.5$ is presented on Figs. 6.1–6.6, from which it is seen, that for colorimetric parameters, specified for UHDTV system, for all luminance levels relative transferred colours area is considerably larger than SDTV and HDTV systems. It can be seen to what degree colour gamut evaluated in uniform (perceptual) colour space depends on the relative luminance *Y* of image detail.

FIGURE 6.1

Colour gamuts of SDTV, HDTV and UHDTV systems for in XYZ space

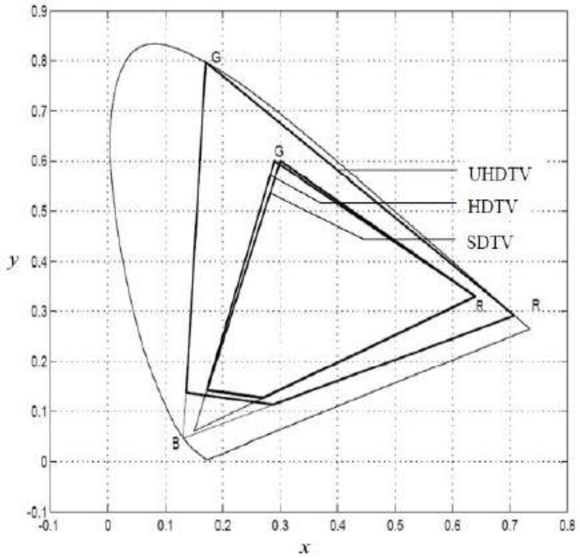


FIGURE 6.2

Colour gamut of SDTV, HDTV and UHDTV systems for and in CAM02-UCS space

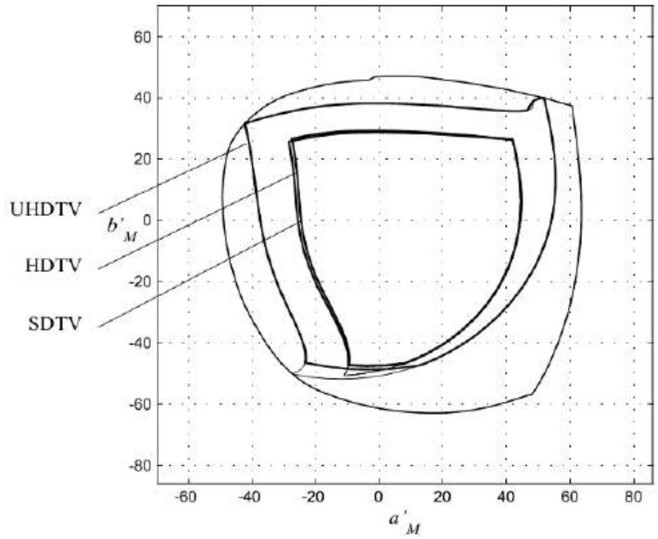


FIGURE 6.3

Colour gamuts of SDTV, HDTV and UHDTV systems for in XYZ space

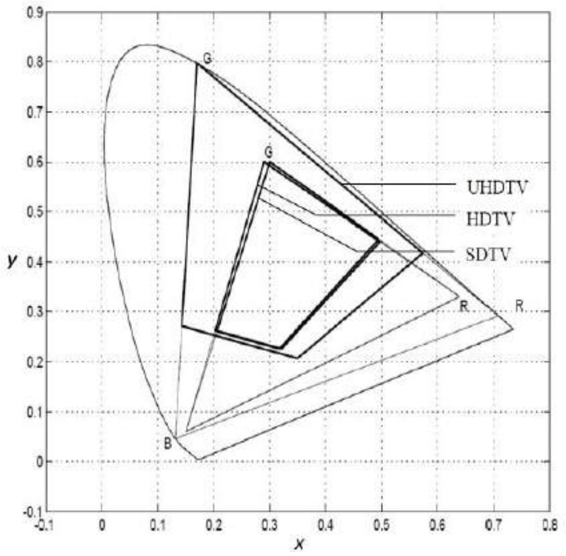


FIGURE 6.4

Colour gamut of SDTV, HDTV and UHDTV systems for and in CAM02-UCS space

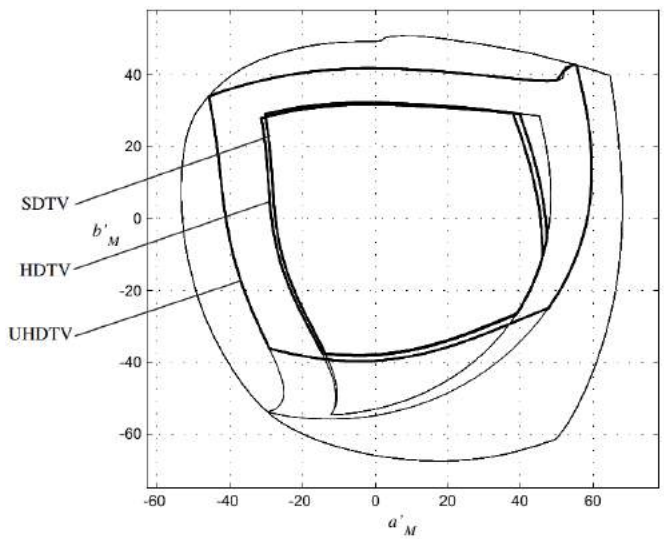


FIGURE 6.5

Colour gamuts of SDTV, HDTV and UHDTV systems for in XYZ space

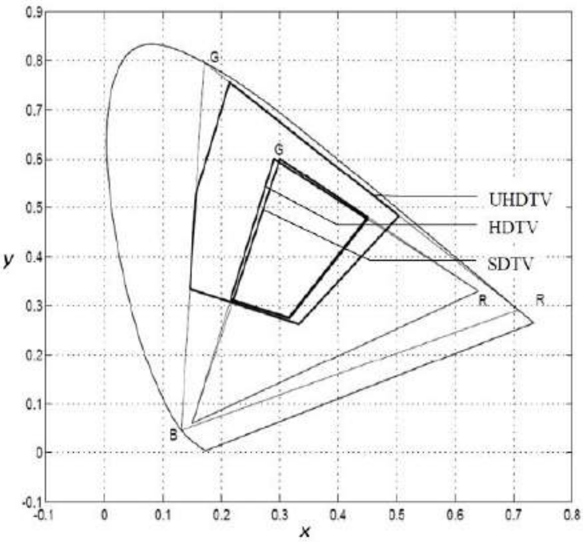
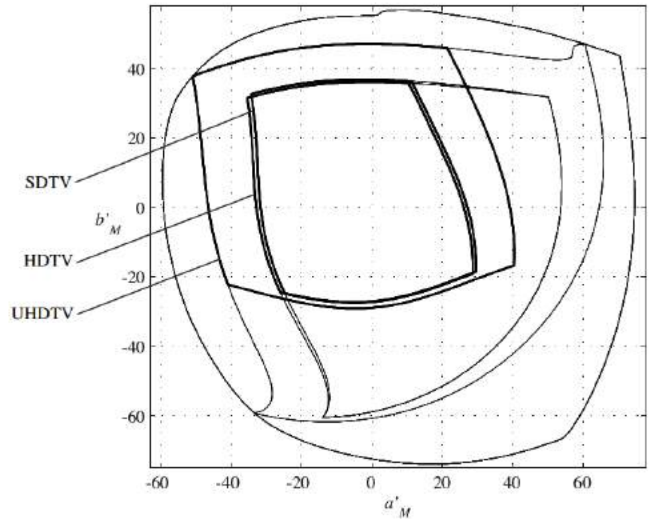


FIGURE 6.6

Colour gamut of SDTV, HDTV and UHDTV systems for and in CAM02-UCS space



6.2 Digital cinema and LSDI applications

Evaluations of colour gamut transmitted by digital cinema (DC) systems and LSDI systems in $\text{CAM02-UCS}(a'_M, b'_M)$ space with consideration of image viewing conditions

Figure 6.7 shows primaries as specified in SMPTE ST 2048-1 [6.7] with chromaticity coordinates presented in the Table 2.6 of Chapter 2. The points of the B and G primaries of the triangle are placed outside the chromaticity diagram, the point of primary R is selected so that it matches the chromaticity diagram boundary point of monochromatic red. So, the area of a primaries triangle exceeds the area of the triangle of UHDTV. Figure 6.7 also shows the projections of area boundaries of transmitted colours on CIE-31 tristimulus values plane. It is seen that for relative brightness of scene details less than 0.25, the major portion of chromaticity diagram area is transmitted.

FIGURE 6.7

Colour gamut boundaries of DC system on the CIE-31 chromaticity diagram plane

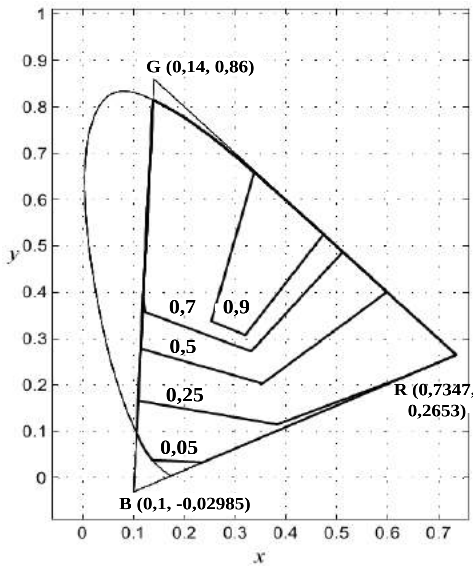


FIGURE 6.8

Area of chromaticities, transmitted by DC system for $L_A = 50$ cd/m^2 presented on the plane of a'_M, b'_M

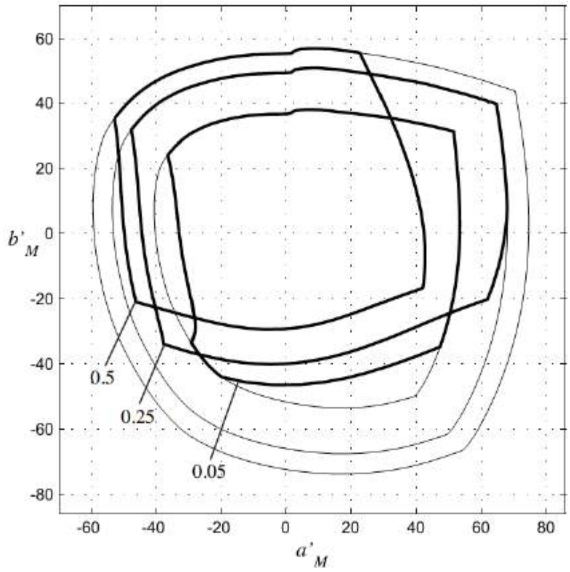


Figure 6.8 presents projections of the transmitted colours area for DC system on the plane of chroma Cartesian coordinates a'_M, b'_M of J', a'_M, b'_M uniform colour space. The projections are presented for the relative luminance levels of 0.05, 0.25, 0.5, 0.7, 0.9 and luminance level on white of 250 cd/m^2, which corresponds to the luminance of the adaptation of observer's visual system respectively equal to 50 cd/m^2.

Figure 6.9 shows primaries triangle of ACES system specified in SMPTE 2065-1 [6.8]. The points of R,G,B primaries of the ACES triangle are placed outside the chromaticity diagram. So all the chromaticity diagram is inside the triangle, and area of ACES triangle is more than area of triangles of DC- system. Figure 6.10 shows the projections of area of transmitted in ACES system chromaticities on CAM02-UCS chromaticity coordinates plane.

FIGURE 6.9

Colour gamut boundaries for ACES system on the CIE-31 chromaticity diagram plane

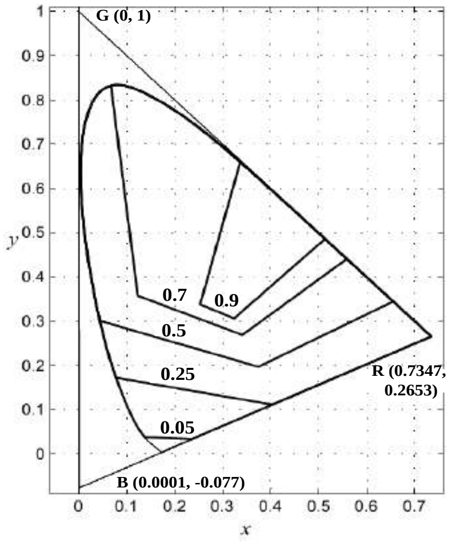
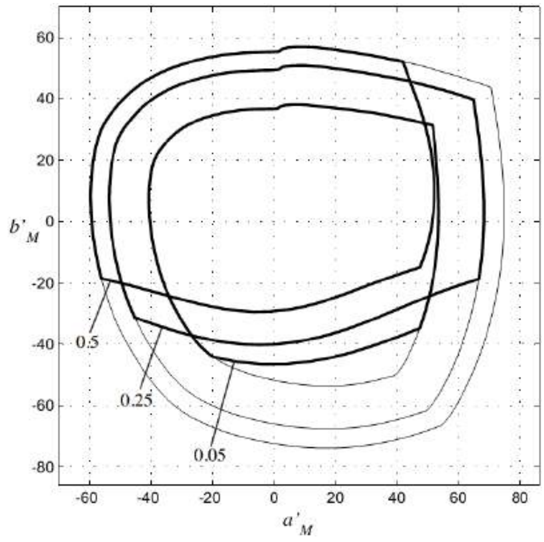


FIGURE 6.10

Area of chromaticities, transmitted by ACES system for $L_A = 50\,\text{cd/m}^2$ presented on the plane of a'_M, b'_M



Extended colour gamut video applications

Systems for extended colour gamut video applications such as RIMM-ROMM Eastman Kodak and Adobe are described in references [6.9–6.11]. Up and till now, they have primarily been used outside the broadcasting industry. However, the broadcast community has discussed over the last years the potential of these systems in programme production, including for screens with more than three primary colours. Evaluation of colour gamut for these applications can be found in [6.13, 6.14].

CHAPTER 7

Possible criteria of colour reproduction quality evaluation

7.1 Approaches to evaluation

The evaluation of quality of colour reproduction should be based on

– the model of the system, for which the evaluation is carried out, and colorimetrical transformations in it;
– viewing conditions of the original scene and displayed image;
– the criteria and procedure of evaluation, including interpretation of results.

In [7.1] six approaches have been formulated for the evaluation of colour reproduction quality.

Spectral colour reproduction

Concerning imaging systems, this approach implies equality of relative spectral power distributions of radiation entering the image capture device and radiation created by display device.

Colorimetric colour reproduction

The purpose of this approach is to achieve equality of chromaticity coordinates and relative luminances of the compared stimuli under the same viewing conditions. Thus, the subjective identity of metameric colour stimuli, i.e. stimuli which that have different spectral power distribution of radiation and the same tristimulus values, is taken into account.

Exact colour reproduction

Such approach requires equality of chromaticity coordinates, relative and absolute luminances of stimuli, being compared, and the radiations of sources of illumination and other parameters affecting the state of adaptation of the visual analyser. Such an approach is used rarely in the real imaging systems, as usually the conditions under which the system operates imply differences of observing conditions at transmitting and receiving ends.

Equivalent colour reproduction

The goal is to achieve equality of chromaticities as well as absolute and relative luminances of colours of the original scene and the reproduced image being viewed under different conditions.

Corresponding colour reproduction

Reproduction, in which chromaticities and relative luminances of colours are such that when seen in the picture-viewing conditions, they have the same appearance as the colours in the original scene would have had if they had been illuminated to produce the same average absolute luminance level as that of the reproduction.

Preferable colour reproduction

The purpose of such an approach is not achievement of strict equality of colour perception of display and standard images, but reproduction of colours in such a way that the colours of the estimated image were more pleasant for an observer than colours of original scene. Reproduction of such ‘memory’ colours has a substantial influence on judgments about reproduced image; however, it cannot be used as independent criterion.

The quality of colour reproduction of large colour image details is most critical, as discriminability of colours increases with the increase of sizes of image details.

Colour, size, form and orientation of details, and also the adapting and masking properties of background and surround, influences the evaluation of quality of colour reproduction of medium and small image details.

7.2 Evaluation criteria of colour reproduction quality

Evaluation of separate colour reproduction quality

For judgments on quality of all image colour reproduction it is desirable to have the assessments of each colour change. For evaluating the quality of specific colour reproduction, large enough uniformly coloured areas of image can be used that allow local effects to be ignored, also the influence of contrast-sensitivity characteristics, descriptions, aureole effects, etc. The distance between the points of colours of original and reproduced image in colour space can serve as the criterion.

Quality evaluation of the reproduction of all varieties of colours

For practical applications, the quality evaluation of integral reproduction of all varieties of colours can be useful. Such evaluations can be made for the range of colours uniformly filling colour space. The root-mean-square, mean absolute, or maximum distance between the points of compared colours in colour space, can serve as a criterion of quality of colour reproduction.

Evaluation of quality of natural scene colour reproduction

Evaluation of the quality of natural scene colour reproduction is complicated due to the problem of choice of test materials. For this purpose the use of images/sequences sets can be used containing images of natural objects with large areas with a few colours, for which the evaluation of colour can be made.

Evaluation of colour reproduction quality in systems with object-oriented presentation of images

In the case of object-based scene presentation, metadata should desirably carry parameter values related to the specific object capturing, processing, transmission, etc. used. Use of object-based presentation of video information implies the possibility of differences in the conditions of capturing, production and processing of separate objects, and in the process of programme production, or some other video processing in the TV light-to-light chain. The possibility of separate object information matching should be provided by metadata, and this information should be brought to the common viewing conditions at the transmission and/or on receiving ends, and this information may be used in the process of image quality evaluation separately for different objects.

Colour reproduction is one of the colour image quality components that can substantially depend on a great number of factors, including characteristics of capture, reproduction, coding, processing, transmission and storage of video information. Thus, the basic method of quality evaluation is subjective evaluation or objective evaluation with the use of devices based on the results of experimental and theoretical research on defining the relation between subjective quality assessments by average observer in the standard viewing conditions and the objective evaluation criteria.

Colour reproduction quality, as a part of general image quality evaluation can be substantially affected by other types of distortions. In this case it can be, in a certain measure, be enhanced by using more perfect models of colour vision for ‘qualimeters’.

Such evaluation is useful to the solving many practical tasks, as it gives an objective judgment of image distortions, and the treatment by observers of concrete types of distortions taking into account their specificity.

As a criterion of colour reproduction quality evaluation, the assessments obtained for test-materials suitably chosen from a colour distortion point of view can be used.

Methods of image quality evaluation for television and multimedia applications are defined in ITU Recommendations [7.2–7.14] and IEC Standards [7.15–7.17].

7.3 Test materials which may be used for the evaluation of colorimetric quality of reproduced images

Recommendation ITU-R BT.1210 [7.5] "The test materials for evaluating image quality" states that the evaluation of image quality can be made with test materials listed in the Report ITU-R BT.2245 [7.19]. The report contains a list of materials, which include still images and sequences of moving images, designed for quality assessment of HDTV systems. Among these pictures, in particular, there are images with the following attributes:

– colour reproduction;

– gray scale reproduction;

– skin colour;

– contrast.

These images may be considered preferable to evaluate image colorimetric quality.

7.4 Optimization of colour reproduction quality for natural objects

In [7.18] the optimization model of natural image colour reproduction quality based on preferable colour reproduction approach is described. It is proposed to evaluate image quality by quality index, defined by naturalness and colorfulness indices. The naturalness index is estimated locally within the three typical of memory colours segments: "skin", "sky" and "grass" on CIELUV chromaticity diagram.

CHAPTER 8

The influence of observing conditions on colour reproduction quality assessment

A difference between scene capturing and image displaying conditions is normal for television and related applications. The influence of image viewing conditions at the receiving end becomes apparent as the change of adaptation of the observer's vision depending on luminance, colour, spatio-temporal and other surround factors, resulting in the potential for distortions of the perceived image colours.

In particular, the illumination conditions of the image display influence perceived image quality greatly due to the screen flare. The flare lowers perceived contrast as it increases the black level. The perceived image colours are also distorted due to the adapting white point shift. There are many works [8.1–8.7] devoted to the influence of illumination on image quality. The CIE Committee TC8-04 "Adaptation under mixed illumination conditions" (http://www.colour.org/tc8-04/) deals with this problem, but research work of this committee is directed mainly on cross-media colour matching (particularly softcopy vs. hardcopy colour matching) [8.8, 8.9]. As for TV field, a method of evaluation of mixed adaptation [8.2], which allows the evaluation of the influence of daylight and interior illumination on displayed colour, can be of interest for television and related applications. A summary of this method is presented below.

The algorithm uses two basic transforms: CIECAM02-based adaptation model (equations (8.1)-(8.5)) and, strictly speaking, accounting for mixed adaptation (equations (8.6)–(8.7)).

The adaptation transform consists of the following steps:

$$\begin{bmatrix} R_1 \\ G_1 \\ B_1 \end{bmatrix} = M_{CAT02} \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} \tag{8.1}$$

where:

$$M_{CAT02} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix}; \qquad D = F\left[1-\left(\frac{1}{3.6}\right)e^{\left(\frac{-L_A+42}{92}\right)}\right];$$

L_A – absolute value of adapting luminance, cd/m^2. If the value of adapting luminance is unknown, it is supposed to be equal to 20% adapting white luminance; F – is the factor for evaluation of degree of observer's adaptation to different surrounds, which equals to 1.0, 0.9 and 0.8 for average, dim and dark surround respectively.

$$R_C = \left[\left(100\,D_1/R_{W1}\right)+\left(1-D_1\right)\right]R_1;\quad G_C = \left[\left(100\,D_1/G_{W1}\right)+\left(1-D_1\right)\right]G_1;\quad R_C = \left[\left(100\,D_1/B_{W1}\right)+\left(1-D_1\right)\right]B_1 \tag{8.3}$$

$$R_2 = R_C/\left[\left(100D_2/R_{W2}\right)+\left(1-D_2\right)\right];\quad G_2 = G_C/\left[\left(100D_2/G_{W2}\right)+\left(1-D_2\right)\right];\quad B_2 = B_C/\left[\left(100D_2/B_{W2}\right)+\left(1-D_2\right)\right] \tag{8.4}$$

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = M_{CAT02}^{-1} \begin{bmatrix} R_2 \\ G_2 \\ B_2 \end{bmatrix} \tag{8.5}$$

Mixed adaptation is evaluated as follows:

$$R_2' = D_{MA}R_2 + \left(1 - D_{MA}\right)R_d; \quad G_2' = D_{MA}G_2 + \left(1 - D_{MA}\right)G_d; \quad B_2' = D_{MA}B_2 + \left(1 - D_{MA}\right)B_d \qquad (8.6)$$

where $R_d G_d B_d$ are the cone responses of the evaluated colour when watching display in dark room, D_{MA} – factor of mixed adaptation:

$$D_{MA} = 1.1119 - \frac{1.1029}{\left(1 + 0.0223L_A\right)^{1/1.3553}}. \qquad (8.7)$$

The algorithm consists of the following steps:

1) Transformation from daylight condition $X_D Y_D Z_D$ to interior condition $X_I Y_I Z_I$ using equations (8.1) – (8.5)

2) Transformation from interior condition $X_I Y_I Z_I$ to mixed adaptation conditions $X_{MA} Y_{MA} Z_{MA}$, using equations (8.1) – (8.5) with substitution $R_2 G_2 B_2$ in equation (8.5) by $R_2' G_2' B_2'$ (equation (8.6)).

The results of experiments [8.2] have shown that, as the adapting luminance goes lower, the correlated colour temperature (CCT) of the adapting white approaches the display's white point. On the contrary, when the adapting luminance increases, the CCT of the adapting white approaches the ambient light's white point. The method considered above allows relatively exact evaluation of changes of colours under mixed adaptation conditions, and the adjustment of display settings suitable to various viewing conditions.

CHAPTER 9

Possible future of TV Colorimetry

The Metrics of the CAM02-UCS system, which is an addition to CIECAM02 system, depends on the human perception of the adapting luminance $L_{\mathrm{A\ Obj}}$ and $L_{\mathrm{A\ Img}}$ for viewing colour objects of the transmitted scene and image of these objects, as well as on the viewing conditions VC_{Obj} and VC_{Img}, on the shooting side and on the reproduction side, which can vary in a wide range independently. So, in this metrics undistorted colour rendering may be formulated as such:

$$J'_{\mathrm{Img}}\Big|_{L_{\mathrm{AImg}},VC_{\mathrm{Img}}} = J'_{\mathrm{Obj}}\Big|_{L_{\mathrm{AObj}},VC_{\mathrm{Obj}}}; \quad a'_{M\ \mathrm{Img}}\Big|_{L_{\mathrm{AImg}},VC_{\mathrm{Img}}} = a'_{M\ \mathrm{Obj}}\Big|_{L_{\mathrm{AObj}},VC_{\mathrm{Obj}}}; \quad b'_{M\ \mathrm{Img}}\Big|_{L_{\mathrm{AImg}},VC_{\mathrm{Img}}} = b'_{M\ \mathrm{Obj}}\Big|_{L_{\mathrm{AObj}},VC_{\mathrm{Obj}}}.$$

This means that it is possible to approach undistorted colour rendering only in systems adaptive to viewing conditions, the main principles of which are specified in Recommendations ITU-R BT.1691 [9.1] and ITU-R BT.1692 [9.2].

In the current chapter, possible principles and examples of construction of adaptive TV and related systems on the base of modern colorimetry are considered for any broadcast and related video applications, in particular for mobile television applications.

Concerning multimedia applications, a standard colour space that can serve as the base for the construction of device-independent applications are defined in the standards IEC 61966-2-1 [9.3] and IEC 61966-2-4 [9.4].

The requirements for adaptive systems for television and related applications are formulated in Recommendations ITU-R BT.1691 and BT.1692. The main idea, problem and examples of implementation of adaptive video applications are presented in Annex C.

As it was previously stated, the viewing conditions greatly influence the perception of reproduced images by display colours. This influence is the most appreciable for mobile and portable applications due to the smaller screen sizes and possible quick changes of luminance and colour parameters of the viewing environment (for example when changing from indoor to outdoor). During such substantial changes of brightness, colorfulness and hue of reproduced colours significant changes in perceptual colour gamut can appear. Traditional methods of colorimetry and qualimetry are not applicable under such conditions. Some examples of the implementation of adaptive TV technologies in mobile and portable applications are presented in Annex D.

CHAPTER 10

The tasks for further studies

Further progress of television colorimetry should be based on more complete implementation of modern colour appearance models and more general human colour vision models on the whole in television and related applications.

TV Colorimetry should be developed in the direction of more complete account of the viewing conditions of images on television screen taking into account spatial, temporal and colorimetric characteristics of the perceived images and their surround.

In particular, the principal question is how the image viewing environment at the transmission and receiving ends, which causes the adaptation of the visual system of observer, can be modelled.

As for the adaptive systems, further studies, directed, on one hand, at the realization of models for adaptive systems and, on the other hand, on the creation of the implementable algorithms of their construction, are necessary.

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1.8 Recommendation ITU-R BT.1692-1:2009 *Optimization of the quality of colour reproduction in digital television*

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2.3 Recommendation ITU-R BT.1700:2005 *Characteristics of composite video signals for conventional analogue television systems*

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Annex A

(relevant to Chapter 3)

New Colour Appearance Models

A.1 CIECAM02 model

The following equations which describe CIECAM02 transformations are based on CIE 159 Report [A.1].

Forward conversion equations

Input data:

X, Y, Z – CIE 1931 tristimulus values of the sample;

X_W, Y_W, Z_W – CIE 1931 tristimulus values for reference white;

L_{SW}, $\mathrm{cd \cdot m^{-2}}$ – surround white luminance;

L_{DW}, $\mathrm{cd \cdot m^{-2}}$ – reproduced image white luminance;

L_A, $\mathrm{cd \cdot m^{-2}}$ – adapting luminance;

if data on adapting luminance are not available it is recommended be taken to be equal to $L_A = 0.2 \cdot L_{DW}$
c – surround impact factor, N_C – chromatic induction factor, F – factor for degree of adaptation, Y_B – relative luminance of the background. If the value of this parameter is unavailable it can be adopted to be equal to $Y_B = 0.2 \cdot Y_W$

If data on c, N_C and F are unavailable they can be chosen as follows.

Viewing conditions and related appropriate parameters of the model

Viewing condition	c	N_C	F
Average surround	0.69	1.0	1.0
Dim surround	0.59	0.9	0.9
Dark surround	0.525	0.8	0.8

Surround type may be defined via such a relationship as: $S_R = L_{SW} / L_{DW}$. The value $S_R = 0$ corresponds to dark surround, $S_R < 0.2$ to dim one and $S_R \geq 0.2$ to average one.

The cone responses are:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \mathrm{M}_{\mathrm{CAT02}} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{A.1}$$

where

$$\mathbf{M}_{\text{CAT02}} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix} \tag{A.2}$$

The degree of viewer's adaptation:

$$D = F \cdot \left[1 - \left(\frac{1}{3.6} \right) \cdot e^{\left(\frac{-(L_A + 42)}{92} \right)} \right] \tag{A.3}$$

The adaptation transform is:

$$R_C = \left[\left(Y_W \cdot \frac{D}{R_W} \right) + (1 - D) \right] \cdot R \qquad G_C = \left[\left(Y_W \cdot \frac{D}{G_W} \right) + (1 - D) \right] \cdot G \qquad B_C = \left[\left(Y_W \cdot \frac{D}{B_W} \right) + (1 - D) \right] \cdot B \tag{A.4}$$

$$k = 1/(5 \cdot L_A + 1) \qquad F_L = 0.2 \cdot k^4 \cdot (5 \cdot L_A) + 0.1 \cdot (1 - k^4)^2 \cdot (5 \cdot L_A)^{1/3}$$

$$n = {}^{Y_B}\!/_{Y_W} \qquad N_{bb} = N_{cb} = 0.725 \cdot (1/n)^{0.2} \qquad z = 1.48 + \sqrt{n}$$

The transformation to Hunt-Pointer-Estevez cone responses is conducted as follows

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \mathbf{M}_{\text{HPE}} \cdot \mathbf{M}_{\text{CAT02}}^{-1} \cdot \begin{bmatrix} R_C \\ G_C \\ B_C \end{bmatrix} \tag{A.5}$$

where:

$$\mathbf{M}_{\text{HPE}} = \begin{bmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.00000 & 0.00000 & 1.00000 \end{bmatrix} \qquad \mathbf{M}_{\text{CAT02}}^{-1} = \begin{bmatrix} 1.096124 & -0.278869 & 1.182745 \\ 0.454369 & 0.473533 & 0.072098 \\ -0.009628 & -0.005698 & 1.015326 \end{bmatrix}$$

The nonlinear response compression transform is:

$$\begin{aligned} R'_A &= \left[400 \cdot (F_L \cdot R'/100)^{0.42} \right] / \left[27.13 + 400 \cdot (F_L \cdot R'/100)^{0.42} \right] + 0.1 \\ G'_A &= \left[400 \cdot (F_L \cdot G'/100)^{0.42} \right] / \left[27.13 + 400 \cdot (F_L \cdot G'/100)^{0.42} \right] + 0.1 \\ B'_A &= \left[400 \cdot (F_L \cdot B'/100)^{0.42} \right] / \left[27.13 + 400 \cdot (F_L \cdot B'/100)^{0.42} \right] + 0.1 \end{aligned} \tag{A.6}$$

If any of values of R', G' or B' are negative, then their absolute values are used and then the corresponding quotient term in Equations (A.6) must be multiplied by a negative 1 before adding the value 0.1.

Opponent axes:

$$a = R'_A - 12 \cdot G'_A/11 + B'_A/11 \qquad b = (1/9) \cdot (R'_A + G'_A - 2 \cdot B'_A) \tag{A.7}$$

Hue angle:

$$h = \tan^{-1}(b/a) \quad h_r = h \cdot 180/\pi \tag{A.8}$$

$$h = \begin{cases} h_r & \text{for} \quad a > 0 \ \& \ b > 0 \\ h_r + 180 & \text{for} \quad a < 0 \\ h_r + 360 & \text{for} \quad a > 0 \ \& \ b < 0 \end{cases} \tag{A.9}$$

Eccentricity factor:

$$e_t = 1/4 \cdot \left[\cos\left(h \cdot \frac{\pi}{180} + 2\right) + 3.8\right] \tag{A.10}$$

Colour quadrature H may be obtained via linear interpolation method:

$$H = H_i + \frac{100 \cdot (h' - h_i)/e_i}{(h' - h_i)/e_i + (h_{i+1} - h')/e_{i+1}} \tag{A.11}$$

using the values of unique hues shown in Table below. Here $h' = h + 360$ if $h < h_1$, and $h' = h$ else wise.

Unique hue data for the calculation of hue quadrature

	Red	**Yellow**	**Green**	**Blue**	**Red**
i	1	2	3	4	5
h_i	20.14	90.00	164.25	237.53	380.14
e_i	0.8	0.7	1.0	1.2	0.8
H_i	0.0	100.0	200.0	300.0	400.0

The achromatic response is:

$$A = \left[2 \cdot R'_A + G'_A - 2 \cdot B'_A\right] \tag{A.12}$$

The lightness is:

$$J = 100 \cdot (A/A_W)^{c \cdot z} \tag{A.13}$$

The brightness is:

$$Q = (4/c) \cdot \sqrt{J/100} \cdot (A_W + 4) \cdot F_L^{0.25} \tag{A.14}$$

The chroma is:

$$C = t^{0.9} \cdot \sqrt{J/100} \cdot \left(1.64 - 0.29^n\right)^{0.73} \tag{A.15}$$

where:

$$t = \frac{(50000/13) \cdot N_C \cdot N_{cb} \cdot e_t \cdot \sqrt{a^2 + b^2}}{R'_A + G'_A + (21/20) \cdot B'_A}$$

The colorfulness is:

$$M = C \cdot F_L^{0.25} \tag{A.16}$$

The saturation is:

$$s = 100 \cdot \sqrt{M/Q}\ . \tag{A.17}$$

CIECAM02 includes three attributes in relation to the chromatic content: chroma (C), colorfulness (M) and saturation (s). These attributes together with lightness (J) and hue angle (h) can form three colour spaces J, a_C, b_C, J, a_M, b_M and J, a_s, b_s, where:

$$a_C = C \cdot \cos(h) \qquad a_M = M \cdot \cos(h) \qquad a_s = s \cdot \cos(h)$$

$$b_C = C \cdot \sin(h) \qquad b_M = M \cdot \sin(h) \qquad b_s = s \cdot \sin(h)$$

A.2 Modification of CIECAM02 by Luo et al.

All the colorimetric assessments based on CIECAM02 are usually expressed in J, C, h or Q, M, h spaces. As it was shown [A.2], usage of J, M, h – space gives more accurate predictions of colour appearance. The following modifications of this space for large (CAM02-LCD), small (CAM02-SCD) and both small and large (CAM02-UCS) colour differences were proposed:

$$J' = \frac{(1+100c_1)\,J}{1+c_1J} \qquad M' = (1/c_2)\ln(1+c_2M) \qquad \text{(A.18)}$$

$$a'_M = M'\cos(h') \quad b'_M = M'\sin(h') \qquad \text{(A.19)}$$

The coefficients for each version of UCS based upon CIECAM02 are the following:

Version of space	CAM02-LCD	CAM02-SCD	CAM02-UCS
K_L	0.77	1.24	1.00
c_1	0.007	0.007	0.007
c_2	0.0053	0.0363	0.0228

As follows from published results of studies [A.2], the estimations obtained with the use of these modifications show the best correlation with all available data on colour appearance and can be considered as basis for the further studies directed to the progress of television and related video applications, and to the progress of colour appearance models for their use as part of the systems of image quality evaluation, in particular, evaluation of colorimetric quality.

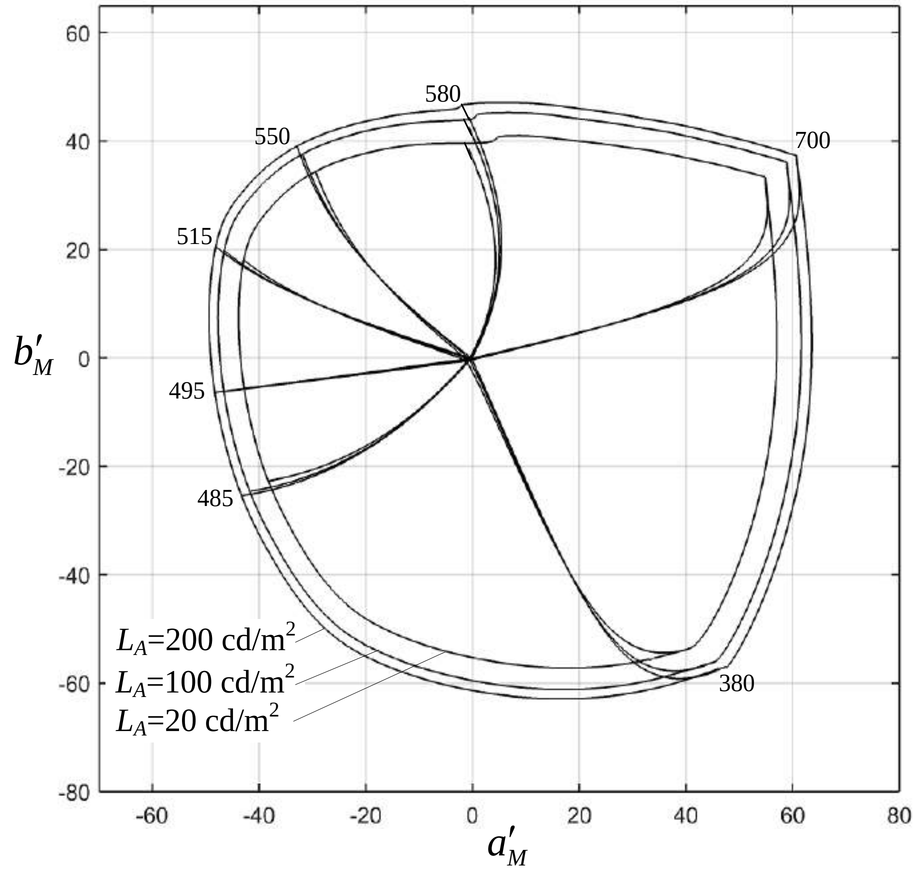
The results of testing published to date have shown that predictions obtained by using CIECAM02-based colour spaces best match all available colour appearance data and can be considered to become a possible base for further research work on development of TV and related video systems, and on the development of colour appearance models for implementation as the part of image quality assessment systems, particularly colorimetric quality assessment.

CAM02-UCS (a'_M, b'_M) chromaticity diagram

CAM02-UCS (a'_M, b'_M) chromaticity diagram [A.3] is presented in Figs A.1 and A.2. The figures demonstrate the dependence of colour appearance on adaptation level L_A and relative luminance level Y in Luo et al. colour space.

FIGURE A.1

Chromaticity diagram CAM02-UCS (a'_M, b'_M), Y_W=100, Y=10



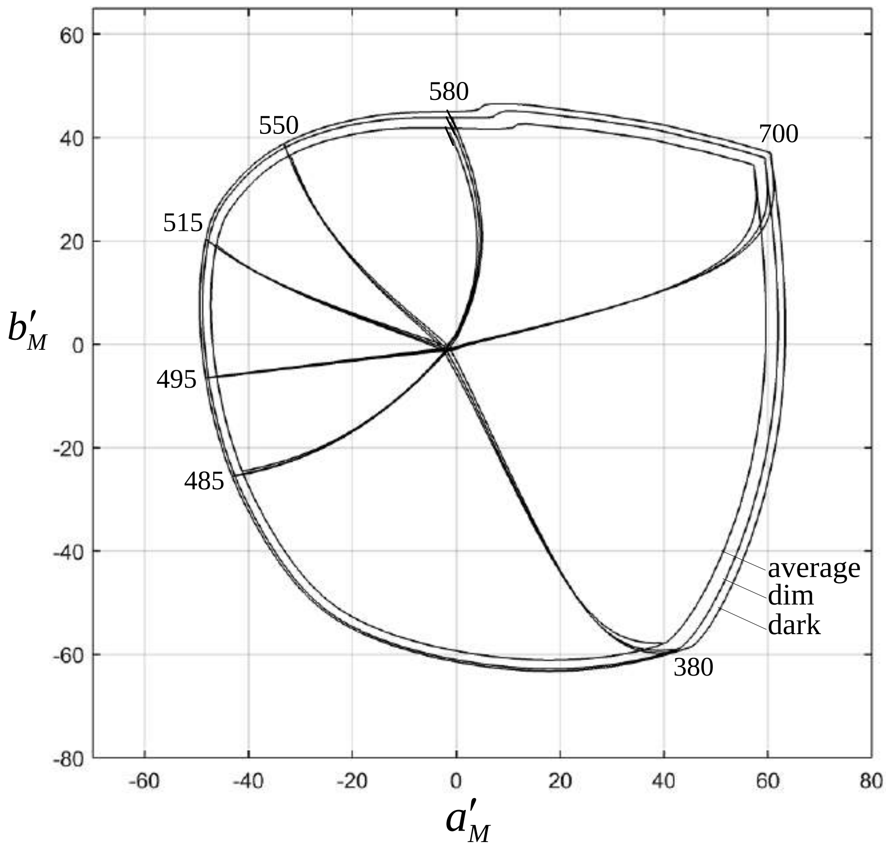
The figures demonstrate change of colour appearance depending on the surround illumination (dark, dim, average) and adapting lightness of L_A for given stimulus luminance relative values Y. As follows from figures, the change of surround may substantially influence on colour appearance. This is clear from the dependence of the projection of the chromaticity diagram on the plane of coordinates a'_M, b'_M and this influence shows up in to the largest degree at large stimulus luminance levels, and the change of both colorfulness (M') and perceived hue (h') can take place.

These changes of colour appearance can be critical for video applications in that viewing conditions substantially differ on transmitting and receiving ends, which results in impairments of colour rendition.

It is possible to give more complete quantitative evaluation of possible colour appearance changes with change of adapting luminance and surround, by an evaluation of the change of chromaticity coordinates in CAM02-UCS space as distance ΔE between points on the plane of coordinates a'_M, b'_M for different combinations of adapting luminance L_A and of surround for the compared stimuli.

FIGURE A.2

Chromaticity diagram CAM02-UCS (a'_M, b'_M)
L_A=20 cd/m^2, Y_W=100, Y=20



The dependence of perceived colours on L_A may be shown with use the criterion:

$$\Delta E_{20-200} = \sqrt{\left(\Delta J'_{20-200}\right)^2 + \left(\Delta a'_{M\ 20-200}\right)^2 + \left(\Delta b'_{M\ 20-200}\right)^2}$$

where $\Delta J'_{20-200}$, $\Delta a'_{M\ 20-200}$, $\Delta b'_{M\ 20-200}$ – differences of coordinates of colour space J', a'_M, b'_M for adapting luminance levels $L_A = 20$ cd/m^2 and $L_A = 200$ cd/m^2.

The values of ΔE_{20-200} are shown in Table A.1. Data, presented on Table A.1 and on Fig. A.2, are comparable with this evaluation. A comparison of evaluations confirms that conditions of independently changing surround of image and adapting luminance at the transmitting side and on a receiving side can result in distortions of colour rendition from a level unnoticeable or barely noticeable to the level of unacceptable impairment of image colorimetric quality.

TABLE A.1

Values of distance ΔE between position of points of monochromatic colours of chromaticity diagram for combined adapting luminance and surround for stimulus luminance, equal 10 cd/m^2

Conditions of viewing (adapting luminance (L_{A1}, L_{A2}) and surround) on capturing and reproduction ends	λ, nm						
	380	**485**	**495**	**515**	**550**	**580**	**700**
$L_{A1} = 200$ cd/m^2 – average $L_{A2} = 20$ cd/m^2 – dim	12.39	8.51	8.4	8.51	8.53	8.59	9.55
$L_{A1} = 200$ cd/m^2 – average $L_{A2} = 20$ cd/m^2 – dark	18.16	13.18	13.01	13.07	13.02	13.02	13.89
$L_{A1} = 20$ cd/m^2 – average $L_{A2} = 200$ cd/m^2 – dim	9.34	9.12	9.01	9.15	9.03	8.63	9.12

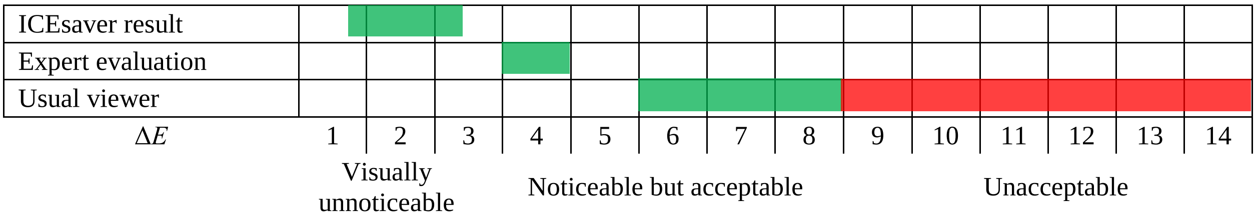
TABLE A.2

Correlation of distance ΔE and colour rendition impairment

ΔE, CIE units	Image impairment evaluation
3	Unnoticeable
5	Barely noticeable
10	Bad
15	Imperceptible

FIGURE A.3

Occurrence of image impairment in dependence of colour deflection levels ΔE



A.3 High-Luminance Colour Appearance Model

High dynamic range imaging systems (HDR-TV) have become more widely used. Evaluation of HDR-systems colorimetry is a complex task as the existing colour appearance models are based on relatively low-luminance experimental data. For instance, the LUTCHI colour appearance data were obtained for luminances up to 690 cd/m^2 (except the small amount of data obtained at 1 000 and 1 280 cd/m^2). CIECAM02 colour appearance model specifically was developed based on this data and it is not intended to operate in very high-luminance domain. In addition, the majority of tone-mapping operators (the transforms necessary for perceptually correct reproduction of HDR-content on low-dynamic range displays) compress luminance range only, without dealing with the colorimetric parameters of images, thus resulting in colorimetric distortions. Thus there is a necessity to create universal colour appearance model that can be applied to high-luminance stimuli. The ref. [A.4] is devoted to one of such kind of model. As the model is still under development, and its formulation in [A.4] has some ambiguities, we give its description just to introduce it. The testing of this model has shown that the accuracy of its predictions at low and average luminance levels is close to CIECAM02 (it is not surprising as this model was created based on CIECAM02 and partially on LUTCHI data); and at high luminance levels (up to 16680 $\mathrm{cd/m^2}$) its performance exceeds CIECAM02.

The model consists of three main components: chromatic adaptation, cone responses, and cortex responses for each perceptual colour attributes. It aims to accurately predict lightness, colorfulness and hue, including the Hunt effect, the Stevens effect, and simultaneous contrast. Additional correlates of brightness, chroma, and saturation will be derived as well.

As the focus of experiments [A.4] was not on chromatic adaptation, CIECAT02 chromatic adaptation transform [A.1] that has been shown to work well was adopted.

To evaluate cone responses tristimulus values are first transformed into LMS cone space using the Hunt-Pointer-Estévez (HPE) transform [A.1]. The cones' absolute responses are modelled as following:

$$L' = L^{n_C} \big/ \left(L^{n_C} + L_A^{n_C} \right), \qquad M' = M^{n_C} \big/ \left(M^{n_C} + L_A^{n_C} \right), \qquad S' = S^{n_C} \big/ \left(S^{n_C} + L_A^{n_C} \right) \qquad \text{(A.20)}$$

where L_A is adaptation level value in $\mathrm{cd/m^2}$. The adaptation level should ideally be the average luminance of the 10° viewing field. The parameter n_c is derived experimentally, $n_c = 0.57$.

The cone response then is converted into an achromatic signal A by averaging the contribution of each type of cone:

$$A = \left(40L' + 20M' + S' \right) / 61 \qquad \text{(A.21)}$$

The lightness is derived by:

$$J' = g\left(A / A_W \right) \qquad \text{(A.22)}$$

with

$$g(x) = \left[-\left(x - \beta_j \right) \sigma_j^{n_j} \big/ x - \beta_j - \alpha_j \right]^{1/n_j}$$

The values of the parameters are derived from experimental data, yielding $a_j = 0.89$, $b_j = 0.24$, $\sigma_j = 0.65$, $n_j = 3.65$. It is interesting to note that J' may yield values below zero, in which case it should be clamped. This corresponds to the case where the observer cannot distinguish dark colours from even darker colours anymore.

As the perceived lightness values vary significantly with different media, the media-dependent lightness value is expressed as:

$$J = 100 \cdot \left[E \cdot \left(J' - 1 \right) + 1 \right] \qquad \text{(A.23)}$$

where the parameter E is different for each medium. A value of $E = 1.0$ corresponds to a high-luminance LCD display, transparent advertising media yield $E = 1.2175$, CRT displays are $E = 1.4572$, and reflective paper is $E = 1.7526$. These parameters were derived from the LUTCHI data set.

The brightness is defined as:

$$Q = J \cdot \left(L_W \right)^{n_q} \qquad \text{(A.24)}$$

The parameter n_q is derived from experimental data, $n_q = 0.1308$.

Preliminary red-green and yellow-blue opponent dimensions are calculated using:

$$a = \frac{1}{11}\left(11L' - 12M' + S'\right); \qquad b = \frac{1}{9}\left(L' + M' - 2S'\right) \tag{A.25}$$

Chroma is calculated as:

$$C = \alpha_k \cdot \left(\sqrt{a^2 + b^2}\right)^{n_k} \tag{A.26}$$

where:

$$\alpha_k = 456.5, \; n_k = 0.62.$$

Colorfulness is defined as:

$$M = C \cdot \left(\alpha_m \log_{10} L_W + \beta_m\right) \tag{A.27}$$

where L_W is reference white luminance, $\alpha_m = 0.11$, $\beta_m = 0.61$.

The other remaining quantity is saturation, which by definition is the colorfulness relative to its own brightness:

$$s = 100\sqrt{M/Q} \tag{A.28}$$

The hue angle is computed by:

$$h = \frac{180}{\pi}\tan^{-1}\left(b/a\right) \tag{A.29}$$

Annex B

(relevant to Chapter 5)

Image appearance models iCAM and MOM

B.1 iCAM

The iCAM image appearance model is a refinement of the CIECAM02 colour appearance model [B.1-B.3]. It omits the sigmoidal compression found in CIECAM02 but adds spatially variant processing in the form of two separate Gaussian-blurred images that may be viewed as adaptation levels. Like most colour appearance models, the model can be applied in the forward direction and in the reverse direction. A flowchart of iCAM image appearance model is shown in Fig. B.1.

As input, the model requires colorimetrically characterized data for the image (or scene) and surrounding in absolute luminance units. The image is specified in terms of relative CIE *XYZ* tristimulus values. The adapting stimulus is a low-pass filtered version of the CIE *XYZ* image that is also tagged with absolute luminance information necessary to predict the degree of chromatic adaptation. The absolute luminances *Y* of the image data are also used as a second low pass image to control various luminance-dependent aspects of the model intended to predict the Hunt effect [B.4] (increase in perceived colorfulness with luminance) and the Stevens effect (increase in perceived image contrast with luminance) [B.5].

Finally, a low-pass, luminance *Y* image of significantly greater spatial extent is used to control the prediction of image contrast that is established to be a function of the relative luminance of the surrounding conditions (Bartleson and Breneman equations). The specific low-pass filters used for the adapting images depend on viewing distance and application.

The first stage of the model is to account for chromatic adaptation. The chromatic adaptation transform embedded in CIECAM02 has been adopted in iCAM since it was well researched and established to have excellent performance with all available visual data.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = M_{CAT02} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \quad M_{CAT02} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix}$$

The amount of adaption is determined by parameter *D*. The *D*-factor can set manually in a range from 0 (no adaptation) to 1 (complete adaptation) or evaluated depending on adapting luminance as expressed below:

$$D = F\left[1 - \left(\frac{1}{3.6}\right)e^{\left(\frac{-L_A - 42}{92}\right)}\right]$$

The adapting white point for each pixel *W(x, y)* is derived from the *XYZ* image by applying a low pass filter with a kernel a quarter the size of the image. This may be applied to each colour channel independently for chromatic adaptation, or on the *Y* channel only for achromatic adaptation. This low-pass filtered image is then also converted with the M_{CAT02} matrix.

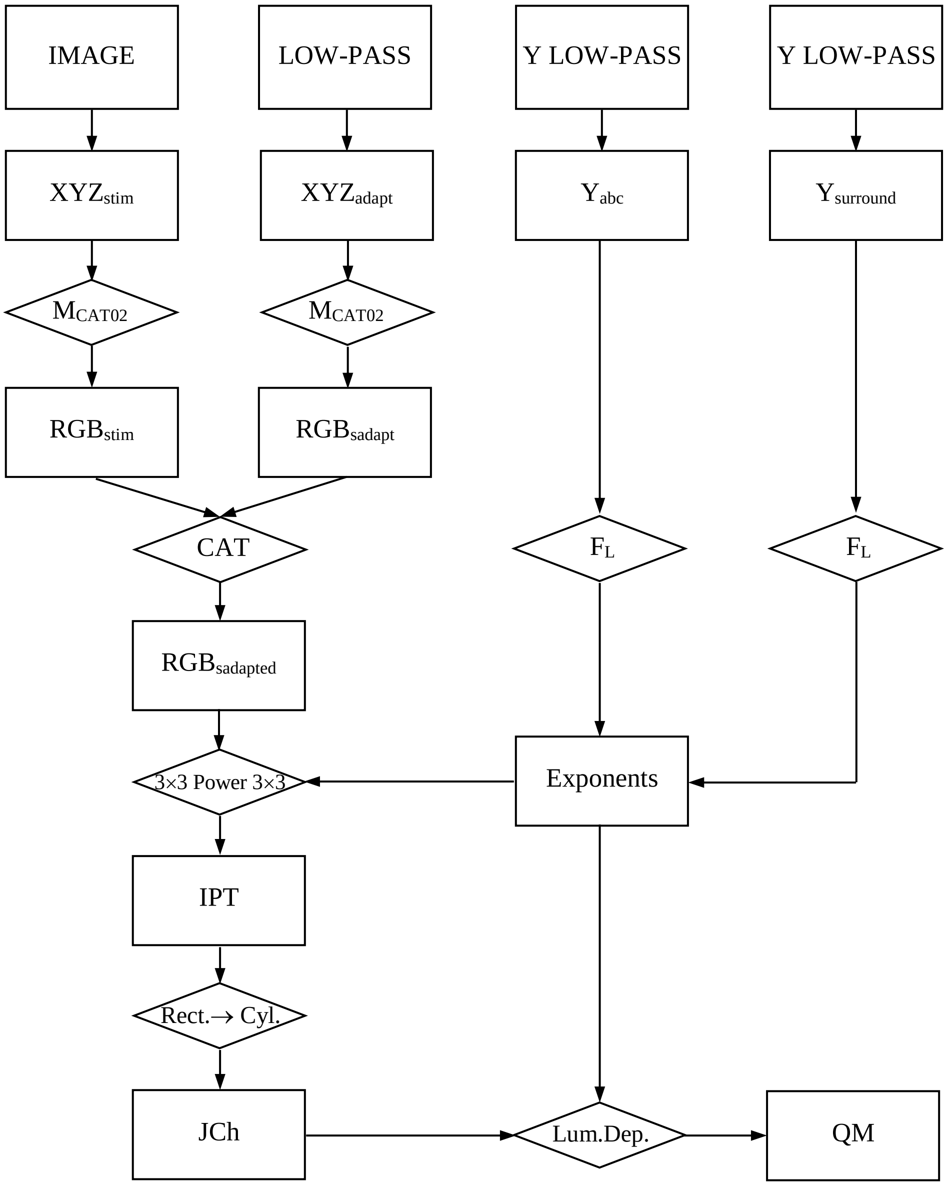
Finally, the D65 white point (95.05, 100.0, 108.88) is also converted to sharpened cone responses. The subsequent von Kries adaptation transform is given by the following.

$$R_c(x,y) = R(x,y)\left(Y_W \frac{D}{W_{R'}(x,y)} + 1 - D\right); \quad G_c(x,y) = G(x,y)\left(Y_W \frac{D}{W_{G'}(x,y)} + 1 - D\right); \quad B_c(x,y) = B(x,y)\left(Y_W \frac{D}{W_{B'}(x,y)} + 1 - D\right)$$

This transform effectively divides the image by a filtered version of the image.

FIGURE B.1

Flowchart of iCAM image appearance model



The next stage of the model is to convert from *RGB* signals to opponent-colour signals that are necessary for constructing a uniform perceptual colour space and correlates of various appearance attributes. The colour space chosen was the *IPT* space that has relatively simple formulation and specifically has a hue angle component with good prediction of constant perceived hue (important in gamut-mapping applications).

The conversion includes such steps:

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.4002 & 0.7075 & -0.0807 \\ -0.2280 & 1.1500 & 0.0612 \\ 0.0 & 0.0 & 0.1984 \end{bmatrix} \begin{bmatrix} X_{D65} \\ Y_{D65} \\ Z_{D65} \end{bmatrix}$$

The exponential function that compresses the range of luminances is given by the following.

$$L'(x,y)=\left|L(x,y)\right|^{0.43F_L(x,y)};\quad M'(x,y)=\left|M(x,y)\right|^{0.43F_L(x,y)};\quad S'(x,y)=\left|S(x,y)\right|^{0.43F_L(x,y)}$$

The exponent is modified on a per-pixel basis by F_L, which is a function of a spatially varying surround map derived from the luminance channel (Y channel) of the input image. The surround map $S(x, y)$ is a low-pass filtered version of this channel with a Gaussian filter kernel size of one-third the size of the image. The function F_L is then given by the following.

$$F_L(x,y)=\frac{1}{1.7}\left(0.2\left(\frac{1}{5S(x,y)+1}\right)^4 5S(x,y)\right)+0.1\left(\left(1-\left(\frac{1}{5S(x,y)}\right)^4\right)^2\sqrt[3]{5S(x,y)}\right)$$

The image is then transformed into *IPT* space:

$$\begin{bmatrix} I \\ P \\ T \end{bmatrix}=\begin{bmatrix} 0.4000 & 0.4000 & 0.2000 \\ 4.4550 & -0.8510 & 0.3960 \\ 0.8056 & 0.3572 & -1.1628 \end{bmatrix}\begin{bmatrix} L' \\ M' \\ S' \end{bmatrix}$$

Once the *IPT* coordinates are computed for the image data, a transformation from rectangular to cylindrical coordinates is applied to obtain image-wise predictors of lightness J, chroma C, and hue angle h:

$$J=I;\qquad C=\sqrt{P^2+T^2};\qquad h=\tan^{-1}\left(\frac{P}{T}\right);\qquad Q=\sqrt[4]{F_L J};\qquad M=\sqrt[4]{F_L C}$$

For image-difference and image-quality predictions, it is also necessary to apply spatial filtering to the image data. The spatial pre-processing serves to eliminate information that is imperceptible to the visual system and normalize colour differences at spatial frequencies that are visible. Since the human contrast sensitivity functions vary for luminance (band-pass with sensitivity to high frequencies) and chromatic (low-pass) information, it is appropriate to apply these filters in an opponent space. Two approaches to use iCAM framework to evaluate image difference are described below.

In image quality applications of iCAM, spatial filtering can be applied in the *IPT* space [B.3]. Since it is appropriate to apply spatial filters in a linear signal space, they are applied in a linear version of *IPT* prior to conversion into the non-linear version of *IPT* for appearance predictions (see Fig. B.2).

However, spatial filtering strongly "blurs" the elements of the image, which is undesirable in cases where viewers watched it closer than the recommended viewing distance.

Example contrast sensitivity functions, used to define spatial filters for image difference computations are given below for the luminance I channel and for the chrominance P and T channels.

$$CSF_{lum}(f)=a\cdot f^c\cdot e^{-bf};\qquad CSF_{chrom}(f)=a_1\cdot e^{-b_1 f c_1}+a_2\cdot e^{-b_2 f c_2}$$

The parameters a, b, and c are set to 75, 0.2, and 0.8 respectively for the luminance CSF, applied to the I channel. The spatial frequency f is defined in terms of cycles per degree of visual angle (cpd). For the red-green chromatic CSF, applied to the P dimension, the parameters ($a1$, $b1$, $c1$, $a2$, $b2$, $c2$) are set to (109.14, 0.00038, 3.424, 93.60, 0.00367, 2.168). For the blue–yellow chromatic CSF, applied to the T dimension, they are set to (7.033, 0.000004, 4.258, 40.69, 0.10391, 1.6487).

The second approach [B.1] to use iCAM framework for image difference assessment (see Fig. B.3) resembles the one used in S-CIELAB. The spatial filtering, allowing for spatial frequency adaptation, is used at the pre-processing stage. Spatial filtering is performed in an orthogonal colour space $Y'C_1C_2$:

$$\begin{bmatrix} Y' \\ C_1 \\ C_2 \end{bmatrix} = \begin{bmatrix} 0.0556 & 0.9981 & -0.0254 \\ 0.9510 & -0.9038 & 0 \\ 0.0386 & 1.0822 & -1.0276 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{D65}$$

The CSF (Contrast Sensitivity Function) used to define spatial filters for image difference computations are given below for the luminance and chromatic channel and chromatic channels

$$\mathrm{CSF}_{lum}(f) = a \cdot f^{c} \cdot e^{-bf}; \qquad \mathrm{CSF}_{chrom}(f) = a_1 \cdot e^{-b_1 f c_1} + a_2 \cdot e^{-b_2 f c_2}$$

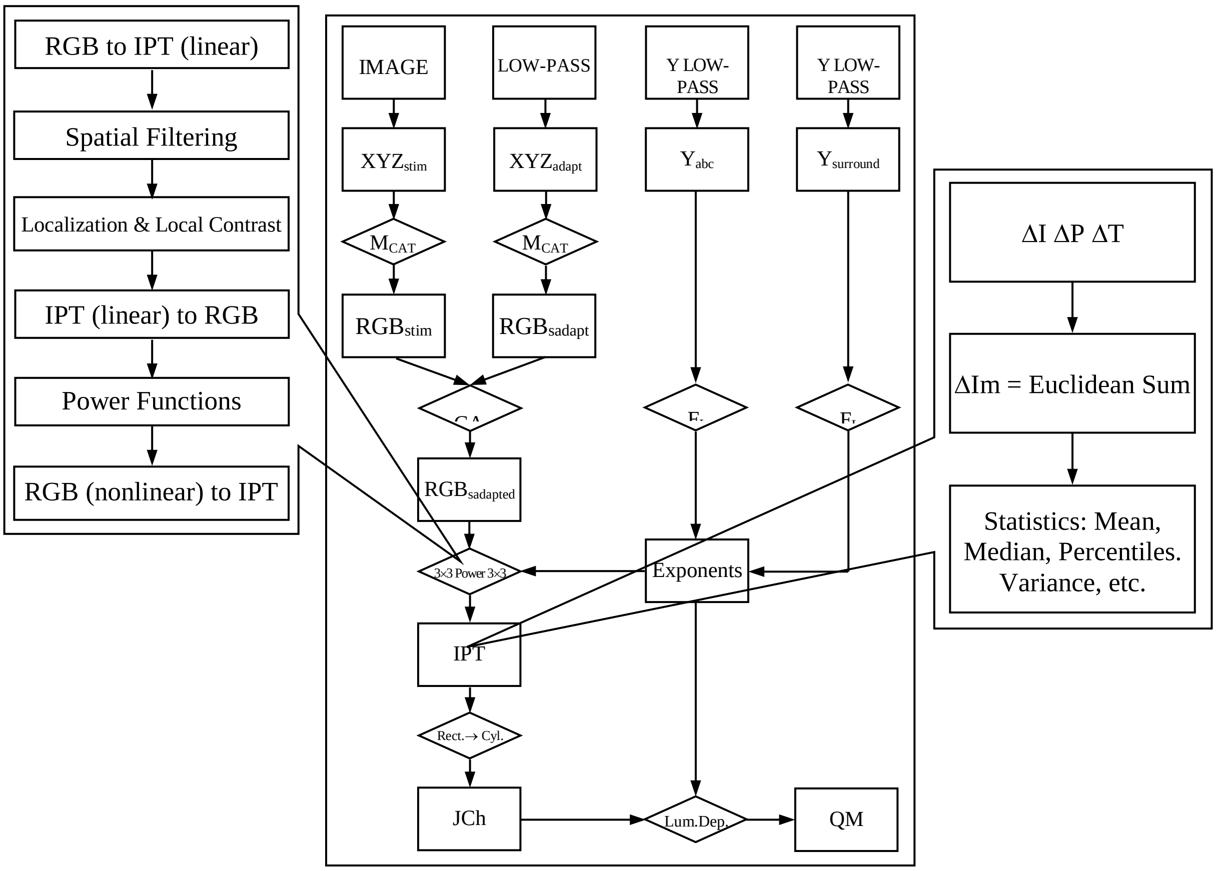
The parameters *a*, *b*, and *c* are set to 75, 0.2, and 0.8 respectively for the luminance CSF. The spatial frequency *f* is defined in terms of cycles per degree of visual angle (cpd).

For the red-green chromatic CSF, applied to the C_1 dimension, the parameters (a_1, b_1, c_1, a_2, b_2, c_2) are set to (91.228, 0.0003, 2.803, 74.907, 0.0038, 2.601). For the blue-yellow chromatic CSF, applied to the C_2 dimension, they are set to (5.623, 0.00001, 3.4066, 41.9363, 0.083, 1.3684).

FIGURE B.2

Implementation of iCAM for image difference and image quality metrics

$$\mathrm{Image}_{\mathrm{filt}} = \mathrm{FFT}^{-1}\left\{\left(\mathrm{FFT}\left\{\mathrm{Image} - \mathrm{mean}\left(\mathrm{Image}\right)\right\}\right) \cdot \mathrm{LumCSF}\right\} + \mathrm{mean}\left(\mathrm{Image}\right)$$



The entire filtering process, for the luminance channel, is shown below.

$$\mathrm{Image}_{\mathrm{filt}} = \mathrm{FFT}^{-1}\left\{\left(\mathrm{FFT}\left\{\mathrm{Image} - \mathrm{mean}\left(\mathrm{Image}\right)\right\}\right) \cdot \mathrm{LumCSF}\right\} + \mathrm{mean}\left(\mathrm{Image}\right)$$

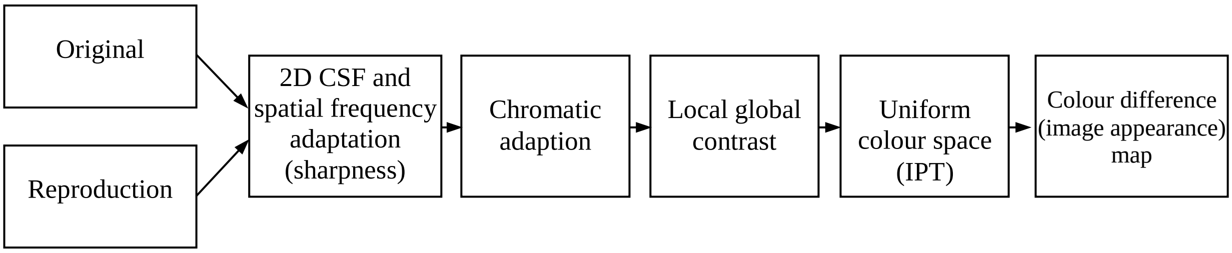
A spatial adaptation mechanism can be described as:

For the red–green chromatic CSF, applied to the C_1 dimension, the parameters (a_1, b_1, c_1, a_2, b_2, c_2) are set to (91.228, 0.0003, 2.803, 74.907, 0.0038, 2.601). For the blue – yellow chromatic CSF, applied to the C_2 dimension, they are set to (5.623, 0.00001, 3.4066, 41.9363, 0.083, 1.3684).

The entire filtering process, for the luminance channel, is shown below.

FIGURE B.3

Implementation of iCAM for image difference and image quality metrics



A spatial adaptation mechanism can be described as:

$$CSF_{\text{adapt}} = CSF \big/ \left(\alpha \cdot \text{FFT}\left(\text{Image}\right) + 1 \right); \qquad \alpha = 1 \big/ \left(D \cdot X_{\text{size}} \cdot Y_{\text{size}} \right)$$

The scaling function, α, converts the frequency representation into absolute units of contrast at each spatial frequency. The D factor is similar to the degree of chromatic adaptation factor found in CIECAM02. Spatial frequency adaptation is important when calculating image differences between images that may have regular periodic patterns, such as a stochastic halftone pattern, or a jpeg-compressed image that has an 8-pixel blocking pattern. The regular period of these patterns actually reduces the visual sensitivity to the pattern itself and makes it less visible. Another potential benefit of spatial frequency adaptation is the ability to predict visual masking without the need for multiscale approaches. If a masking frequency is present in an image, the CSF for that particular frequency region (depending on the extent of the blur) will become less sensitive.

To calculate appearance difference the filtered images are then processed using the general iCAM framework discussed above. This results in two pixel-by-pixel colour appearance maps. These colour appearance maps are in a uniform colour space and as such can be used to calculate perceived colour differences through simple subtraction.

Often the differences must be characterized by one number. This is done mainly on the basis of statistical data on the colour differences, such as the mean, standard deviation and higher confidence intervals (e.g. 95 %). Total ΔIm Euclidean difference in the IPT space is defined as:

$$\Delta Im = \sqrt{\left(100\,\Delta I\right)^2 + \left(150\,\Delta P\right)^2 + \left(150\,\Delta T\right)^2}.$$

Coefficients 100 and 150 are used to match the range of differences with a range of CIELAB.

B.2 MOM

The Multiscale Observer Model is designed to be a complete model of spatial vision and colour appearance [B.2]. It is capable of taking into account a wide range of visual phenomena, including high-dynamic range, tone-mapping, chromatic adaptation, luminance adaptation, spreading, and crispening.

The first step in the forward model is to account for light scatter in the ocular media, followed by spectral sampling to model photoreceptor output. This yields four images representing the rods and the L, M, and S cones. These four images are then each spatially decomposed into seven-level Gaussian pyramids and subsequently converted into four six-level difference-of-Gaussian (DoG) stacks that represent band pass behaviour as seen in the human visual system. DoGs are computed by subtracting adjacent images in the pyramid.

The next step consists of a gain control system applied to each of the DoGs in each of the four channels. The shape of the gain control function resembles TVI curves such that the results of this step may be viewed as adapted contrast pyramidal images.

The cone signals are then converted into a colour opponent scheme that contains separate luminance, red-green, and yellow-blue colour channels. The rod image is retained separately.

Contrast transducer functions that model human contrast sensitivity are then applied. A colour appearance map is formed next, which is the basis for the computation of the aforementioned appearance correlates.

To obtain DoGs, the model calls for low-pass filtered copies with spatial frequencies of 0.5, 1, 2, 4, 8, and 16 cycles per degree (cpd). The model expects input to be specified in LMS cone coordinates and *R* rod coordinates. Stack of six DoG images that represent adapted contrast at six spatial scales is defined as following

$$L_s^{\mathrm{DoG}}(x,y)=\left(L_s^{\mathrm{blur}}(x,y)-L_{s+1}^{\mathrm{blur}}(x,y)\right)G\left(L_{s+1}^{\mathrm{blur}}(x,y)\right)$$
$$M_s^{\mathrm{DoG}}(x,y)=\left(M_s^{\mathrm{blur}}(x,y)-M_{s+1}^{\mathrm{blur}}(x,y)\right)G\left(M_{s+1}^{\mathrm{blur}}(x,y)\right)$$
$$S_s^{\mathrm{DoG}}(x,y)=\left(S_s^{\mathrm{blur}}(x,y)-S_{s+1}^{\mathrm{blur}}(x,y)\right)G\left(S_{s+1}^{\mathrm{blur}}(x,y)\right)$$
$$R_s^{\mathrm{DoG}}(x,y)=\left(R_s^{\mathrm{blur}}(x,y)-R_{s+1}^{\mathrm{blur}}(x,y)\right)G\left(R_{s+1}^{\mathrm{blur}}(x,y)\right)$$

where *s* denotes the level of filtering,

$L_s^{\mathrm{blur}}(x,y), M_s^{\mathrm{blur}}(x,y), S_s^{\mathrm{blur}}(x,y), R_s^{\mathrm{blur}}(x,y)$ – the coordinates of filtered images.

G - compressive function applied in all stages of the Multiscale observer model is given by the following gain control.

$$G(L)=\frac{1}{0.555(L+1)^{0.85}};\quad G(M)=\frac{1}{0.555(M+1)^{0.85}};\quad G(S)=\frac{1}{0.555(S+1)^{0.85}};\quad G(R)=\frac{1}{0.555(S+1)^{0.85}}$$

The low-pass image at level *s* = 7 is retained and will form the basis for image reconstruction. In the final step of the forward model, pixels in this low pass image are adapted to a linear combination of themselves and the mean value $\bar{L}_7^{\mathrm{blur}}(x,y), \bar{M}_7^{\mathrm{blur}}(x,y), \bar{S}_7^{\mathrm{blur}}(x,y)$ of the low-pass image, as follows:

$$L_7^{\mathrm{blur}}(x,y)=L_7^{\mathrm{blur}}(x,y)G\left((1-A)\bar{L}_7^{\mathrm{blur}}+AL_7^{\mathrm{blur}}(x,y)\right)$$
$$M_7^{\mathrm{blur}}(x,y)=M_7^{\mathrm{blur}}(x,y)G\left((1-A)\bar{M}_7^{\mathrm{blur}}+AM_7^{\mathrm{blur}}(x,y)\right)$$
$$S_7^{\mathrm{blur}}(x,y)=S_7^{\mathrm{blur}}(x,y)G\left((1-A)\bar{S}_7^{\mathrm{blur}}+AS_7^{\mathrm{blur}}(x,y)\right)$$

The amount of dynamic range reduction is determined by user parameter *A* in these equations, which takes a value between 0 and 1.

To obtain the perception correlates and to prepare the image for the display, the inverse model is to be applied.

In the first step of the inverse model, the mean white point $L_{\mathrm{d,mean}}, M_{\mathrm{d,mean}}, S_{\mathrm{d,mean}}$ of the target display device needs to be determined. A gain control factor is determined, and the low-pass image is adapted once more, but now for the mean display white point as follows.

$$L_7^{\text{blur}}(x,y) = \frac{L_7^{\text{blur}}(x,y)}{G(L_{\text{d,mean}})}; \qquad M_7^{\text{blur}}(x,y) = \frac{M_7^{\text{blur}}(x,y)}{G(M_{\text{d,mean}})}; \qquad S_7^{\text{blur}}(x,y) = \frac{S_7^{\text{blur}}(x,y)}{G(S_{\text{d,mean}})}$$

The stack of DoGs is then added to the adapted low-pass image one scale at a time, starting with $s = 6$ and followed by $s = 5, 4, \ldots, 0$, as follows.

$$L_7^{\text{blur}}(x,y) = \max\left(L_7^{\text{blur}}(x,y) + \frac{L_s^{\text{DoG}}(x,y)}{G\left(L_7^{\text{blur}}(x,y)\right)},\ 0 \right)$$

$$M_7^{\text{blur}}(x,y) = \max\left(M_7^{\text{blur}}(x,y) + \frac{M_s^{\text{DoG}}(x,y)}{G\left(M_7^{\text{blur}}(x,y)\right)},\ 0 \right)$$

$$S_7^{\text{blur}}(x,y) = \max\left(S_7^{\text{blur}}(x,y) + \frac{S_s^{\text{DoG}}(x,y)}{G\left(S_7^{\text{blur}}(x,y)\right)},\ 0 \right)$$

The reconstruction of a displayable image proceeds by successively adding bandpass images back to the low-pass image. These bandpass images by default receive equal weight. It may be beneficial to weight bandpass images such that higher spatial frequencies contribute more to the final result. Although the original Multiscale observer model does not feature such a weighting scheme, we have found that contrast in the final result may be improved if higher frequencies are given a larger weight. The scale factor k used for these images relates to the index number s of the bandpass pyramid in the following manner.

$$k = (6 - s)g$$

The constant g is a user parameter, which we vary between 1 and 5. A larger value for g produces more contrast in the tone-mapped image, but if this value is chosen too large the residual halos present in the image are emphasized.

Finally, the result is converted to XYZ and then to RGB, where gamma correction is applied.

The computational complexity of this operator remains high, and we would only recommend this model for images with an extreme dynamic range. If the amount of compression required for a particular image is less, simpler models likely suffice. The model can be simplified, by computing three colour channels.

Annex C

(relevant to Chapter 9)

Problems and example of adaptive TV technologies implementation

This Annex considers possible future systems which adapt themselves to the viewing environment.

C.1 The problems of realization adaptive systems implementation

The peculiarity of construction of adaptive systems is that to provide the perceptual realism of transmitted scenes in television, it is necessary to provide for the corresponding variation of viewing conditions at the receiving end. It will be partially realized by means of implementation of some large screen systems.

From a point of view of technical realization of adaptive principles in systems of different levels, the problem is to define standard colour space which may be constructed to be adaptive to different television scene types; this is the principle difference to existing multimedia applications. Perhaps, there will be some colour spaces, being chosen depending on information transmitted in digital flow. It should be the subject of further studies.

One of the problems is to obtain information on viewing conditions at the receiving end. The conditions can be complicated, so characterization based on relative white luminance only is a very limited criterion. There is not enough information available to make further enhancements yet. It should be also the subject of further studies.

There are also difficulties with the determination of the viewing conditions at the receiving side, as knowledge about light and colour adaptation is limited.

There is still the possibility of using CIECAM02 colour appearance model for adapting TV system to adapting luminance and background luminance, but these parameters describe the perception conditions only partially.

Still, the use of such possibility as realization of standard colour space on the basis of modern colour appearance model like CIECAM02 can allow creation TV systems with correct colorimetry and that seem to be the step for further progress of TV systems.

C.2 An example of adaptive technology implementation

In [C.1] the description of the Java applications compensating influence of illumination of displayed image colours implemented on MHP-platform for set-top boxes is presented. The applications described in [C.1] perform the illumination compensation based on the limited set of viewing conditions which user can choose from. In a more advanced version of application user can set luminance and colour temperature of illumination source and gamma-value of halftone reproduction curve. The transition to target viewing conditions is performed on the basis of CIECAM02 colour appearance model using 3D colour look-up tables. The authors of [C.1] noted the suitability of use of Java program language to integrate the applications with MHP platform and expressed the opinion that it is very promising approach for developing adaptive image quality control applications for TV set-top boxes.

Annex D

(relevant to Chapter 9)

Mobile applications

As it was previously stated, the viewing conditions influence the perception of reproduced by display colours greatly. This influence is most noticeable for mobile and portable applications, due to the smaller screen sizes and possible quick changes of luminance and colour parameters of the viewing environment (for example when changing from indoor to outdoor). During substantial distortions of brightness, colorfulness and hue of reproduced colours changes in perceptual colour gamut can appear. Traditional methods of colorimetry and qualimetry are not applicable under such conditions. This section is devoted to the problems of mobile applications colorimetry and to the compensation of influence of viewing conditions.

D.1 CIECAM02 for mobile applications

In [D.1] the applicability of CIECAM02 colour appearance model for evaluation of colorimetry of mobile applications was tested. The experiments were conducted for three types of displays: 2' mobile phone display, 4' PDA display and 7' LCD display for four types of surround: dark, dim, average and bright. Bright surround corresponds to surround ratio value S_R >1. Testing has shown that CIECAM02 performance for mobile applications is insufficient, especially for bright surround (that is expected as CIECAM02 was developed for dark, dim and average surrounds only). Each of the surround type is characterized by a fixed value set of parameters c, N_C and F . To raise the accuracy of predictions, the following continuous functions of dependence of these parameters on surround were proposed in [D.1]:

$$\begin{aligned} c' &= 0.023S_R + 0.7887 \\ F' &= -0.003S_R + 1.1474 \\ N'_C &= 0.0203S_R + 1.2369 \end{aligned} \qquad \text{(D.1)}$$

The testing has shown that using of these functions improves the model performance.

D.2 Illumination-adaptive colour reproduction system for mobile displays

In [D.2] a method of compensation of influence of illumination on appearance of colours reproduced by mobile display is described. The method consists of the following steps:

The lux sensor is built into a mobile phone to detect ambient light intensity. According to the measured intensity level, the amount of flare, expressed as the CIE *XYZ* values, are calculated. Then, for the luminance component, lightness enhancement is implemented by establishing a linear relationship between the luminance values and the cone response values to obtain perceived tone reproduction, where the cone response values corresponding to the luminance value are simply calculated from the lightness adaptation model. Then the chroma compensation is done by adding the chroma values reduced by the flare to those of original image, yielding a colourful image. Since this kind of serial-based procedure is not appropriate for real-time processing, a look-up table representing daylight intensity is designed based on the sampled RGB data.

In the CIE 122-1996, flare is defined as the portion of the ambient light reflected from the display panel and is added to the colours produced by the mobile LCD:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{Display}} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{LCD}} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{Flare}} \tag{D.2}$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{Flare}} = R \cdot \frac{M}{\pi} \frac{1}{y_{\text{ambient}}} \begin{bmatrix} x_{\text{ambient}} \\ y_{\text{ambient}} \\ 1 - x_{\text{ambient}} - y_{\text{ambient}} \end{bmatrix}, \tag{D.3}$$

where *R* is the reflection ratio of the display screen (between 0.5 % and 2 % for mobile LCD) and ($x_{\text{ambient}}, y_{\text{ambient}}$) is the chromaticity of the ambient light; *M* is the intensity of the ambient light (lux) taken from the lux-sensor.

Lightness enhancement is carried out by the following procedure. An input *RGB* value is converted into a *XYZ* value by using piecewise linear interpolation. Lightness enhancement is executed only for the luminance component of the *XYZ* value, while the remainder of the components are left intact. First, the flare is added with an input luminance value, which is then mapped to a cone response by using the lightness adaptation model.

$$Y = Y_{\text{image}} + Y_{\text{flare}} \tag{D.4}$$

$$R_{cone} = f(Y) = \frac{Y^n}{Y^n + \sigma^n} \tag{D.5}$$

where Y_{image} and Y_{flare} are the luminance values of the input image and flare, respectively.

σ is the half-saturation parameter (i.e. the value that causes half of the system's response, $Y = 0.5$) and *n* is a sensitivity constant. To compute *σ* the following empirical relationship can be used [D.3]:

$$\sigma = I_{\text{A}}^{\alpha} \times \beta, \tag{D.6}$$

Where α is 0.69 and σ is the value between 5.83 and 2.0 cd/m^2, depending on what receptor (cone or rod) is considered [D.3] I_{A} – ambient intensity (in cd/m^2).

The corresponding luminance (Y') for the cone response (R_{cone}) is found through linearization of the input luminance (Y) to establish a linear relation between input luminance and cone response for the lightness enhancement. Linearized cone response can be acquired by exchanging the cone response with the input luminance using piecewise linear interpolation. The sampled input luminance values $(y_0, y_1, \ldots y_n)$ are transformed to a cone response value $(R_{cone,0}, R_{cone,1}, \ldots R_{cone,n})$ using equation (F.5). These cone response values are normalized to an amount of one and are stored in one-dimensional (1D) look-up table (LUT). For an arbitrary input luminance value, piecewise linear interpolation is applied to the 1D LUT, thus creating the output cone response curve. Then, inverse cone response curve is simply obtained by switching the cone response value with the luminance value stored in 1D LUT. Therefore, a new input value R'_{cone} for the inverse cone response can be calculated as follows:

$$R'_{cone} = \left(\frac{Y_{\max} - Y_{\min}}{R_{\max} - R_{\min}} \right) \cdot (R_{cone} - R_{\min}) \tag{F.7}$$

Finally, the corresponding luminance (Y') for the input value R'_{cone} can be obtained by applying the piecewise linear interpolation to the 1D LUT. This value is then combined with the intact colour components and is transformed into the CIELCH colour space for the subsequent application of the chroma compensation.

To compensate the chroma, the chroma difference between two types of environment, i.e., darkroom and outdoors, is added to the CIELCH (in [D.2] the CIELAB colour space was used) value acquired from lightness enhancement. However, since the chroma difference depends on the hue value, chroma compensation should be applied considering each chroma value individually.

$$C_{diff} = C - C_{flare} \quad \text{(D.8)}$$

$$C' = C + \alpha C_{diff} \quad \text{(D.9)}$$

where C and C_{flare} are the chroma values from darkroom and outdoor environment respectively. The compensated chroma is adjusted according to the enhancement parameter α to prevent the compensated chroma value falling outside the colour gamut boundary.

$$\alpha = \begin{cases} 1 & \text{if } C < \left(C_{gamut} - \beta \cdot C_{diff}\right) \\ \dfrac{\left(C_{gamut} - C\right)}{\beta \cdot C_{diff}} & \text{otherwise} \end{cases} \quad \text{(D.10)}$$

where β is the compression starting point parameter and C_{gamut} is the gamut boundary calculated by using the method developed by Braun and Fairchild [D.4]. This method uses gridding and interpolation to arrive at a data structure consisting of a uniform grid in terms of lightness and hue, and it stores the gamut's most extreme chroma values for each of the grid points. The boundary value has 101 and 360 levels for each grid points. If the input chroma value is inside $C_{gamut} - \beta \cdot C_{diff}$, the chroma difference is added to the input chroma value without compression. Otherwise, compression compensation is executed by using the compression starting point parameter β, which can be set flexibly values of 1.0, 1.5, and 2.0. If β is over 2.0, chroma compensation is not effective through the experiment, while a clipping artefact is generated if the value is less than 1.0 [D.2]. Finally, the 3D RGB lookup table should be composed for real-time processing.

The results of experiments [D.2] have shown quite good performance of the lightness enhancement and chroma compensation algorithm for mobile LCD, thus reproducing more colourful and brighter images in the outdoor environment. Furthermore, the authors of the algorithms expect that they can be applied to other portable devices.

D.3 Image Colour-Quality Modelling for Mobile LCDs

This clause describes the development of an image colour quality model based on individual physical image statistical measures for mobile liquid crystal displays [D.5].

In this model only colour attributes were considered and the accumulated mean opinion score (MOS) values of image quality from the previous study were used to develop an image colour-quality model based on image statistical measures such as memory colour reproduction, mean chroma and 95th percentile lightness. The spatial attributes were left for future research.

The model uses the similarity of the colour considered compared to its memory prototype as quality criterion. It is comprised of three parts: quantifying memory colour, chroma, and lightness. It is capable of predicting the quality of individual images in respect of colour variation. Each of the attributes affecting image quality was modelled separately and all three were combined into a single image colour-quality model. The concept of region of interest (ROI) was adopted at this point. Basically, it is assumed that when the ratio of reproduced colours in an ROI that are similar to its memory prototype is higher, the image should exhibit higher image quality.

The internal memory prototype can be defined in terms of a colour centre and a tolerance. The colour centre is the mean colour coordinates of a certain memory colour and the tolerance is a level of acceptable colour difference unit from this colour centre. The scene-dependency effect in image quality judgment can be compensated by those two factors.

The concept of region of interest (ROI) was adopted at this point. It is assumed that when the ratio of reproduced colours in an ROI that are similar to its memory prototype is higher, the image should exhibit higher image quality. To highlight the ROI (e.g. face, foliage, sky etc.) the masking can be applied.

The model calculation of the memory colour reproduction ratio (MCRR) is defined as the ratio of reproduced colours in a particular ROI, of which colour difference from its colour centre is less than the given tolerance, as shown in equation below.

$$MCRR = \frac{1}{m}\sum_{x=0}^{X-1}\sum_{y=o}^{Y-1} cat\left(x, y\right) \tag{D.11}$$

where X and Y are the numbers of horizontal and vertical pixels in the image considered and $cat\left(x,y\right)$ is a binary number at each pixel in an input image, i.e. 1: within tolerance or 0: out of tolerance. The total number of pixels categorized into the ROI is m.

The colorfulness model $\left(C_Y\right)$ is based on summation of mean and standard deviation of saturation in CIELAB space:

$$\bar{C}_{ab}^* = \frac{1}{XY}\sum_{i=0}^{X}\sum_{j=0}^{Y}\sqrt{\left(a_{ij}^{*2} + b_{ij}^{*2}\right)} \tag{D.12}$$

$$\Delta\bar{E}_n = \frac{1}{XY}\sum_{i=0}^{X}\sum_{j=0}^{Y}\sqrt{\left(\left(L_{ij}^* - 50\right)^2 + a_{ij}^{*2} + b_{ij}^{*2}\right)} \tag{D.13}$$

$$C_Y = \frac{1}{XY}\sum_{i=0}^{X}\sum_{j=0}^{Y}\left(\sqrt{\left(a_{ij}^{*2} + b_{ij}^{*2}\right)}\right) + \sigma \tag{D.14}$$

where X and Y are the numbers of horizontal and vertical pixels in the image considered. L^*, a^*, b^* represent the CIELAB coordinates for each pixel of the image and σ is the standard deviation of C_{ab}^* for the pixels in image.

For predicting lightness influence on image quality, the 95th percentile L^* was proposed as it has shown the highest correlation with MOS for image tested.

The colour image quality model can be derived by combining the three main effects [D.5] (memory colour reproduction ratio in a region of interest, mean chroma and 95th percentile lightness) with the following manner:

$$IQ_{CQ} = \begin{bmatrix} a & b & c & d & e & f & g & h \end{bmatrix} \begin{bmatrix} M \\ C \\ L \\ M \times C \\ M \times L \\ C \times L \\ M \times C \times L \\ 1 \end{bmatrix} \quad \text{(D.15)}$$

where M is Ln($MCCR$), C is C^*_{ab} and L is 95th percentile lightness L^*.

The coefficients for the metric are listed below:

Coefficients	**Value**
a	8.85
b	−0.47
c	−9.37
d	−0.63
e	−10.04
f	0.62
g	0.84
h	11.57

As it was shown in [D.5] the model is capable of appraising a single image with a good correlation without the presence of an original image. It is also important that subjective image quality was linked to objective values such as image statistical characteristics.