Advanced Colorimetry of Display Systems: Tetra-Chroma[3] Display Unit

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Abstract. *High-fidelity color image reproduction is one of the key issues in visual telecommunication systems, for electronic commerce, telemedicine, digital museum and so on. All colorimetric standards of display systems are up to the present day trichromatic. But, from the shape of a horseshoe-area of all existing colors in the CIE xy chromaticity diagram it follows that with three real reproductive lights, the stated area in the CIE xy chromaticity diagram cannot be overlaid. The expansion of the color gamut of a display device is possible in a few ways. In this paper, the way of increasing the number of primaries is studied. The fourth cyan primary is added to three conventional ones to enlarge the color gamut of reproduction towards cyans and yellow-oranges. The original method of color management for this new display unit is introduced. In addition, the color gamut of the designed additive-based display is successfully compared with the color gamut of a modern subtractive-based system. A display with more than three primary colors is called a multiprimary color display. The very advantageous property of such display is the possibility to display metameric colors.*

Keywords

Colorimetry, color image reproduction system, primaries, chromaticity diagram, multiprimary display, spectral matching.

1. Introduction

The color gamut of contemporary display systems covers no more than 50% of the color gamut of all real colors. If for the correct scan of the whole color information three color paths are sufficient, then for the reproduction of every existing color an "infinite" number of reproductive lights with chromaticity coordinates lying on the border curve (spectrum locus) of the CIE xy chromaticity diagram is necessary. *Infinite* was given in quotation marks because in a real finite number of reproductive lights as a consequence of limited color differences perception would be sufficient. It is evident that the display device with a color gamut including all existing colors can be fully utilized only in the case of true input color information. Such information is offered e.g. by XYZ Color Splitting System [1].

From the practical colorimetric point of view, a main drawback of contemporary CRT or LCD display systems is impossibility of reproduction of cyan and saturated orange-yellow colors, which can be readily achieved by other imaging system, e.g. ink-jet printing [2], [3], [4], [5]. Now, in time when the utter majority of all print outputs is prepared or started in graphic application on a computer, it means via CRT or LCD display, the disadvantage is clear – a graphic designer cannot fully control the print outputs through the computer monitor. This problem is partially solved by so-called *soft-proofing* that is based on the transforms between color spaces of corresponding devices. It means that for proofing, the whole reproduction chain has to be calibrated and profiled. For example, a graphic designer creates an image in an application supporting a color management system and creates it e.g. in the Adobe RGB (1998) color space. Consecutively, the finished work should be printed on an ink-jet printer, e.g. Epson Stylus Pro 7600 & Epson Ultrachrome inks, with an ink-jet photo paper, e.g. Ilford Glossy RC paper, in a resolution of 1440 x 720 dpi via stochastic raster. If the designer wants to see the estimated result from the printer on the monitor, he has to make a soft-proofing as follows. An image in the Adobe RGB (1998) color space is normally displayed through a monitor icc profile on the screen. In the case of soft-proofing of the stated printer and paper, the image from the Adobe RGB (1998) color space has to be converted with a suitable rendering intent (relative colorimetric or perceptual) into the color space, which is a combination of a used printer, inks, a paper, a resolution and a screening algorithm. This converted image is then displayed on the screen through a monitor profile with an appropriate rendering intent (relative or absolute). It is basically a preview of the final output. As referred earlier, a main weakness of soft-proofing lays on a small gamut of contemporary display systems, primarily in cyans and orange-yellows. This drawback can be overcome through an expansion of a color gamut of display systems. Then, a simulation of a final output on a monitor would become very effective.

2. Tetra-Chroma Display Unit

The position of contemporary 3 primaries (in terms of a chromaticity diagram) is given by compromise to cover the area of the most frequently occurred colors with a given reproduction triangle. As for the green primary light in the contemporary reproductive triangle, in contrast to the blue and red primary, is the most compromisingly located to achieve satisfactory reproduction of yellows as well as cyans. Due to this compromise, cyans and orange-yellows that are achievable in printing are not reproducible by contemporary trichromatic display systems. As referred earlier, this leads to a poor function of soft-proofing systems.

The reproduction of really all existing colors is not desirable in every task since very often a given imaging system cannot generate (or transmit) such color gamut and then statistical redundancy of signals driving the display increases and a gamut of reproduction is not exploited. By looking at a contemporary reproduction triangle in the CIE xy or CIE u'v' chromaticity diagram, it is evident, that the addition of the fourth reproduction light into an area of cyans has a cardinal significance. Thanks to this cyan reproductive light, the green reproductive light would be shifted towards the spectrum locus similarly as in the case of NTSC standard. It means that the choice of a new cyan primary light carries an advantageous position for the green primary. The contemporary sRGB reproductive triangle and the new proposed RGCB tetragon are shown in Fig. 1. The position of R and B primary is in the case of RGCB the same as in the sRGB specification. A new position of the **G** primary is $x_G = 0.26$, $y_G = 0.7$, and the new **C** primary has chromaticity coordinates as follows: $x_C = 0.05$, $y_C = 0.6$. The primary lights were not chosen too spectral to be achievable through different technologies. From the spatial resolution point of view, the addition of the fourth primary light still ensures the reach of the desired resolution not only for TV but also for graphic, fine art and scientific applications. Contemporary possibilities of graphic cards and given displays allow trouble-free adding of the fourth light – the graphic cards offer a sufficient capacity and displays have so small image pixels that one picture element, which today consists of 3 pixels, can be created by four pixels without a loss of quality in spatial resolution.

The crucial task in the case of more than tri-chroma display unit is obtaining suitable control signals that drive the brightness of the display primaries [6], [7]. An input signal, typically X, Y, Z tristimulus (accurately electrical analogues of CIE XYZ tristimulus) is converted into a control signal, **c**, with the number of elements $3 + N_{DF}$, where N_{DF} represents a number of the degree of freedom. In other words, it is a task where there are fewer equations than unknowns, that is, the underdetermined case, and an infinite number of solutions exist. Of these solutions, there are two with a great practical value. First, the solution that has a maximum number of zeros in the elements of the control signal **c**. The second solution gives a control signal **c** where the length or norm of **c** is smaller than other possible solutions. This solution, based on the pseudoinverse, is called the minimum norm solution.

In our case of the tetra-chromatic display system, a number of degrees of freedom $N_{DF} = 1$ and then the solution that has the maximum number of zeros passes into the case of a trichromatic system when always one from the four primaries has its brightness equal to zero. This only mathematic solution is not utilizable in a real display system because such solution does not encompass the necessary condition about the reference white light – this reference light has to be only one and has to lie in the gamut of given three primaries (into the triangle created by these three primaries). On the basis of Fig. 1, it can be found out that e.g. $\mathbf{D_{65}}$ reference light is included only into triangles RGB and RCB and not in BGC and RGC reproduction triangle.

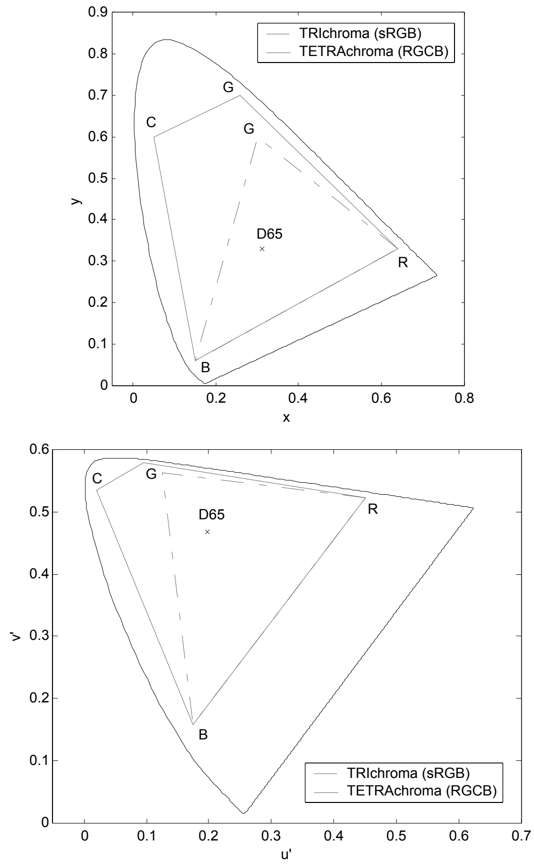


Fig. 1. Conventional sRGB and proposed RGCB color gamut in CIE xy (top) and CIE u'v' (bottom) chromaticity diagram.

The minimum norm solution does not give only non-negative values of elements of control signal, **c**, and from this reason, such solution is not system applicable in a real display, too. The negative brightness of primaries cannot be made. In Fig. 2 below there is shown the area, which is covered in the case when all four primaries (elements of **c**) are non-negative. It can be readily seen that the minimum norm solution together with the condition about non-negative brightness of primaries does not ensure the reproduction of the desired color gamut. This reproducible area is marked grey in the chromaticity diagram in Fig. 2.

The two presented solutions – with a maximum number of zeros and with a minimum norm do not lead to the suitable control signal, **c**, which could be used for driving of display primaries. The solution applicable in a real display system will be introduced in following subsections.

This new solution is based on the division of the given RGCB tetragon into triangles and offers a corresponding colorimetric conversion. In addition, a *virtual primary* is established. The term virtual does not mean non-feasible; it means the primaries that are not physically implemented in the display. The division of the RGCB region into desired sub-regions (in terms of 2D chromaticity diagram) has to satisfy the condition that the reference white light has to be only one and has to lie within each sub-region of RGCB tetragon (**D$_{65}$** reference light is chosen). The condition about reference light can be said also from the other side: The reference white light, which needs to be only one in a given display system, has to be able to be reproducible (colorimetrically matched) via all sub-regions, from which the color gamut of the display system is assembled.That way, the continuity between individual color sub-gamuts (sub-regions) of the main (RGCB) color gamut is achieved. The following solution named *Tetra-chroma^3 Display Unit* introduces one virtual primary. The virtual primary is modeled by real (in display physically implemented) primaries.

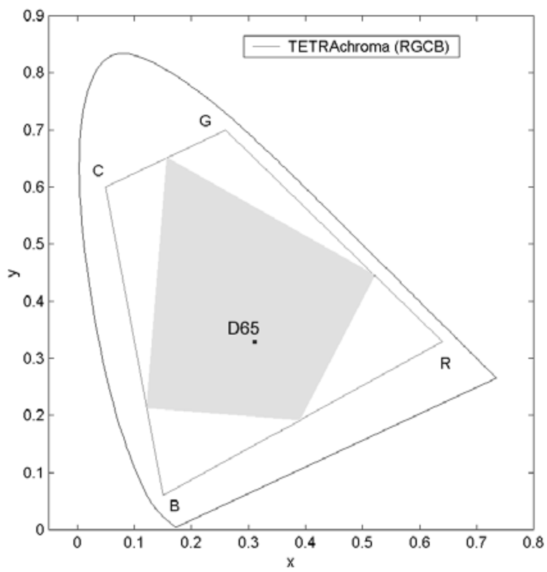


Fig. 2. Reproducible area (grey) as a result of minimum norm solution with condition about non-negative elements of the control signal **c**.

3. Tetra-Chroma^3 Display Unit

The RGCB reproductive tetragon is divided into three triangles. The two – RGB and RCB – are created by real primaries and the last – GCM – uses one virtual primary. The CIE xy chromaticity coordinates of these primaries are in Tab. 1 and their positions in the CIE xy chromaticity diagram are shown in Fig. 3. The virtual primary, magenta **M**, lies on the midpoint of the connecting line between **R** and **B** primaries (in terms of CIE xy chromaticity system, see Eq. 1).

$$x_M = (x_R + x_B)/2,$$
$$y_M = (y_R + y_B)/2. \qquad (1)$$

This position guarantees that the chosen reference light, **D$_{65}$**, lies inside of GCM triangle and then unambiguous, in real system practicable, colorimetric conversion XYZ ↔ GCM according to common colorimetric conversion matrix (Eq. 2 below) exists.

Primaries of Tetra-chroma^3 Display		
CIE xy	**x**	**y**
R	**0.64**	**0.33**
G	**0.26**	**0.70**
C	**0.05**	**0.6**
B	**0.15**	**0.06**

Virtual primary of Tetra-chroma^3 Display		
CIE xy	**x**	**y**
M	**0.395**	**0.195**

Reference white light		
CIE xy	**x**	**y**
D$_{65}$	**0.3127**	**0.3290**

Tab. 1. CIE xy chromaticity coordinates of used primaries and reference light in Tetra-chroma^3 Display Unit.

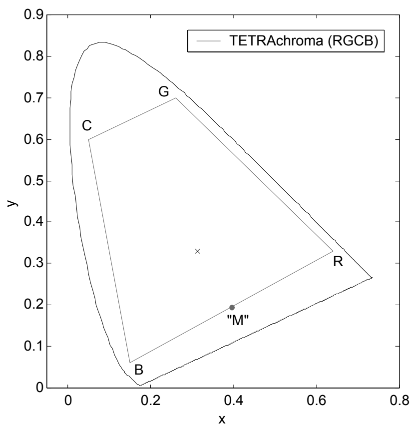


Fig. 3. Primaries of Tetra-chroma^3 Display Unit in the CIE xy chromaticity diagram.

The three above stated sub-regions, RGB, RCB and GCM, in which the RGCB Tetra-chroma^3 Display Unit is separately driven, are overlaid each other. For example, the area around the reference light can be reproduced with the help of all three triangles (this follows from the earlier referred condition about the reference white light). On the contrary, the areas of saturated cyans, greens and yellows are reproducible always through only one triad of primaries of Tetra-chroma^3 Display Unit. Just these areas are not reproducible by contemporary trichromatic display systems. The RGB, RCB and GCM sub-regions are marked in chromaticity diagrams in Fig. 4 below and the overlapping of individual sub-regions is also illustrated.

3.1 Control Signals for the Tetra-Chroma^3 Display Unit

Mathematical interpretation of common colorimetric transformation is calculated by using of Eq. 2 [8]. In this illustrative case, it deals with colorimetric transformation from CIE XYZ tristimulus values of the colorimetric system of $(\mathbf{X}, \mathbf{Y}, \mathbf{Z})_{CIE}$ primaries into A, B, C tristimulus values of the colorimetric system of (**A**, **B**, **C**) primaries.

$$A = \begin{vmatrix} X & x_B & x_C \\ Y & y_B & y_C \\ Z & z_B & z_C \end{vmatrix} \Bigg/ \begin{vmatrix} x_W/y_W & x_B & x_C \\ 1 & y_B & y_C \\ z_W/y_W & z_B & z_C \end{vmatrix},$$

$$B = \begin{vmatrix} x_A & X & x_C \\ y_A & Y & y_C \\ z_A & Z & z_C \end{vmatrix} \Bigg/ \begin{vmatrix} x_A & x_W/y_W & x_C \\ y_A & 1 & y_C \\ z_A & z_W/y_W & z_C \end{vmatrix}, \qquad (2)$$

$$C = \begin{vmatrix} x_A & x_B & X \\ y_A & y_B & Y \\ z_A & z_B & Z \end{vmatrix} \Bigg/ \begin{vmatrix} x_A & x_B & x_W/y_W \\ y_A & y_B & 1 \\ z_A & z_B & z_W/y_W \end{vmatrix}$$

where x_A, y_A, z_A, resp. x_B, y_B, z_B, resp. x_C, y_C, z_C, and x_W, y_W, z_W are x, y, z chromaticity coordinates of **A**, resp. **B**, resp. **C** primaries and reference white **W**. As shown in Eq. 2, for common colorimetric transformation the expression of the "new" primaries (**A**, **B**, **C**) in the "old" colorimetric system (CIE XYZ) has to be known.

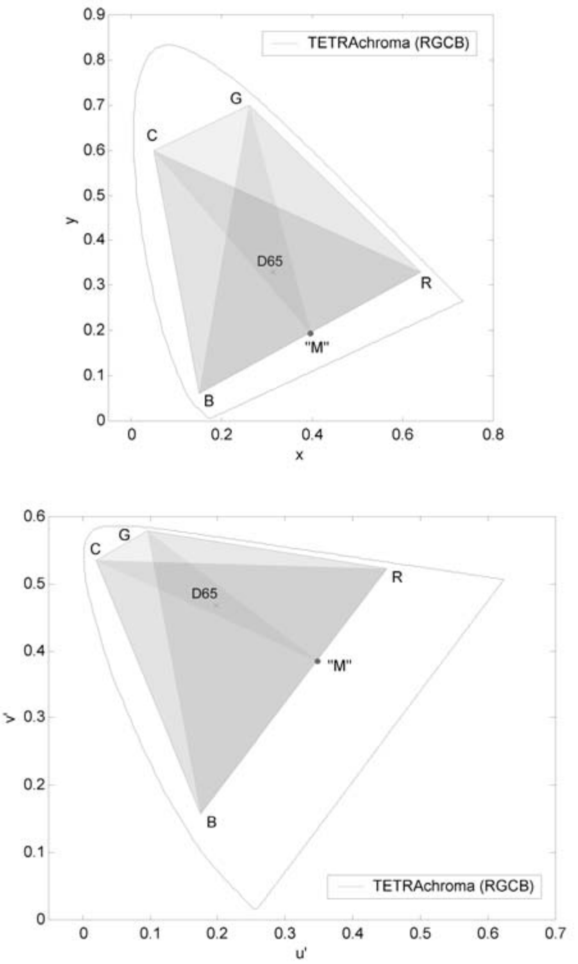


Fig. 4. Three sub-regions of RGCB tetragon of Tetra-chroma^3 Display Unit shown in CIE xy (top) and CIE u'v' (bottom) chromaticity diagrams.

Individual colorimetric transformation between CIE XYZ tristimulus (inputting information) and RGB, RCB and GCM tristimulus (desirable information for the display primaries driving) are computed according to (2) and are given by (3A-C). The tristimuli resulted from these equations represent elements of the corresponding control signal, **c**. The continuity between individual RGB, RCB and GCM color sub-gamuts of RGCB color gamut is ensured by option such sub-gamuts, that the chosen reference white light (in our case $\mathbf{D_{65}}$) lies inside of each sub-gamuts.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix}_{Tetra-chroma^3} = [T_{RGB}] \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{CIE}$$

$$\text{where} \quad [T_{RGB}] = \begin{bmatrix} 2.4303 & -0.8801 & -0.3946 \\ -0.9692 & 1.8760 & 0.0416 \\ -0.0211 & -0.0482 & 0.9809 \end{bmatrix}, \qquad (3A)$$

$$\begin{bmatrix} R \\ C \\ B \end{bmatrix}_{Tetra-chroma^3} = [T_{RCB}] \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{CIE}$$

$$\text{where} \quad [T_{RCB}] = \begin{bmatrix} 1.2987 & 0.0373 & -0.2494 \\ -0.9692 & 1.8760 & 0.0416 \\ 0.3606 & -0.8229 & 1.3591 \end{bmatrix}, \qquad (3B)$$

$$\begin{bmatrix} G \\ C \\ M \end{bmatrix}_{Tetra-chroma^3} = [T_{GCM}] \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{CIE}$$

$$\text{where} \quad [T_{GCM}] = \begin{bmatrix} 4.5338 & 3.0034 & -5.7964 \\ -3.9135 & 1.2727 & 3.1650 \\ 0.8741 & -0.3520 & 0.4786 \end{bmatrix}. \qquad (3C)$$

The transforms output control signals in range <0,1> which are relative to their 100% amount (e.g. $R = G = B = 1$) that is used for the reference white light matching. The highest amounts (the absolute bright rate) of the primaries in individual sub-gamuts correspond to components of the equation of the luminance signal matching (4A to 4C).

$$Y_{RGB} = [0.2633 \quad 0.6586 \quad 0.0780] \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{Tetra-chroma^3} \qquad (4A)$$

$$Y_{RCB} = [0.3947 \quad 0.5496 \quad 0.0556] \cdot \begin{bmatrix} R \\ C \\ B \end{bmatrix}_{Tetra-chroma^3} \qquad (4B)$$

$$Y_{GCM} = [0.2296 \quad 0.3581 \quad 0.4124] \cdot \begin{bmatrix} G \\ C \\ M \end{bmatrix}_{Tetra-chroma^3} \qquad (4C)$$

Eqns. (4A) to (4C) follow from inverse transforms to the transforms in (3A) to (3C). I.e., for white light matching through GCM sub-gamut, the primaries have the following bright proportion

$Y_G : Y_C : Y_M = 0.2296 : 0.3581 : 0.4124$
and $Y_G + Y_C + Y_M = 1$.

3.2 Reproduction of the Virtual Primary

The driving of the virtual primary, magenta **M**, is based on the reproduction of this primary via **R** and **G** primaries. The procedure is as follows. When the reproduction with help of GCM sub-gamut is required, the transformation given by Eq. 3C is performed. The result of this transform, the GCM tristimulus, is modified to obtain the XYZ tristimulus of the **M** virtual primary. For this purpose, the **G** and **C** values of the GCM tristimulus are set to zero and then with help of the inverse transform to Eq. 3C, XYZ_M tristimulus of the **M** virtual primary is obtained. With the XYZ_M tristimulus it is then operated as with a standard final light (the light to be reproduced). It means that Eq. 3A or 3B is used to obtain the R and B stimulus of the **R** and **B** primary that reproduce the **M** virtual primary (G or C stimulus in Eq. 3A or 3B are in this case zeros since the **M** virtual primary lies on the connectivity line between **R** and **B** primaries). It means that in the case of reproduction of the final light using the GCM sub-gamut, all four in display physically implemented primaries are utilized. The whole process of computing of the desired control signals of the Tetra-chroma[3] Display Unit is now described if the GCM color sub-gamut is used for reproduction.

Firstly, the GCM tristimulus given by Eq. 3C of the light to be reproduced is computed. From this result, final values (control signals) for **G** and **C** primaries are obtained. Then from the GCM tristimulus, where the G and C values are set to zero, the XYZ_M tristimulus of the **M** virtual primary is computed through the inversion transform to the transform in Eq. 3C. This operation is given by

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_M = \left[T_{GCM}^{INV}\right] \cdot \begin{bmatrix} 0 \\ 0 \\ M \end{bmatrix} \tag{5}$$

where $\left[T_{GCM}^{INV}\right] = inv\left(\left[T_{GCM}\right]\right) = \begin{bmatrix} 0.0853 & 0.0298 & 0.8354 \\ 0.2296 & 0.3581 & 0.4124 \\ 0.0131 & 0.2089 & 0.8671 \end{bmatrix}.$

Now, according to (3A) or (3B), the RGB or RCB tristimulus for the virtual primary reproduction is obtained. Because the **M** virtual primary lies on the connectivity line between **R** and **B** primaries, G or C values are in the case of the **M** primary light matching zeros. The R and B values work from Eq. 3A and 3B differently since these values are relative to their maximum amount which is used for reference white light matching. In other words, R and G stimuli work from Eq. 3A and 3B differently only in the mathematical point but from the colorimetrically point of view, R and G stimuli computed from both equations match in the color of the same quantity and quality.

3.3 Sphere of Activity of Individual Sub-gamuts of the Tetra-chroma[3] Display Unit

Besides determination of control signals for primaries of Tetra-chroma[3] Display Unit, the sphere of activity of individual sub-gamuts, RGB, RCB, and GCM, should be chosen. The determination of the spheres of activity is the consequence of the individual sub-gamuts overlapping. There is a large number of possibilities since the criteria about reproduction of the final lights, which lie in areas where two or all three sub-gamuts overlap, can differ. One possibility is graphically illustrated in Fig. 5. This is based on the very simple criterion – on the spatial position (in terms of chromaticity diagram) of the final light (the light to be reproduced), where the highest priority has the RGB sub-gamut and the lowest priority has the GCM one.

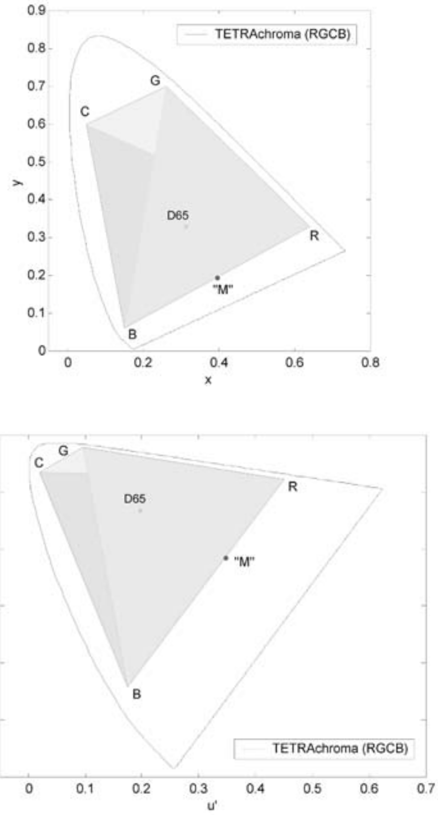


Fig. 5. One possibility of division of RGCB color gamut of Tetra-chroma[3] Display Unit into sphere of activity of individual sub-gamuts shown in CIE xy (top) and CIE u'v' (bottom) chromaticity diagram.

On the contrary, a very sophisticated criterion is based on the spectral matching. This method takes advance of more than tri-chroma display systems if the inputting information about an original light is described not only in colorimetric domain, but also in spectral domain. The aim is a reproduction of a light that matches with its original not only colorimetrically but also spectrally [9], [10]. Multispectral recording is required in this case as well as spectral distributions of used display primaries have to be known. The main aim of such method is discounting observer metamerism [10]. For example, the original light can be reproduced through all three triads of primaries that create a base of the corresponding color sub-gamuts – RGB, RCB, and GCM. I.e., given light reproduced individually by these three sub-gamuts matches in color from colorimetric point of view – metameric colors are reproduced. The criterion of choosing of the sub-gamut, through which the reproduced light best matches with its original in color also from spectral viewpoint, is given by

$$\min\left(\mathbf{f} - \sum_{i=1}^{3} \mathbf{c}_i \cdot \mathbf{p}_i\right) \tag{6}$$

where **f** is the spectrum of the original light, and

$$\sum_{i=1}^{3} \mathbf{c}_i \cdot \mathbf{p}_i$$

is the spectrum composed from the primaries that participate on the original light reproduction. The $\mathbf{c}_i = (c_1, c_2, c_3)$ marks control signals for the primaries driving and is calculated from Eq. 3 above, and $\mathbf{p}_i = (p_1, p_2, p_3)$ represents the spectrum of the corresponding primaries. It means that on the basis of the criterion (6), one triad of primaries (one sub-gamut) with the corresponding control signal is chosen – either $\mathbf{p}_1 = (p_R, p_G, p_B)$ with $\mathbf{c}_1 = (c_R, c_G, c_B)$ or $\mathbf{p}_2 = (p_R, p_C, p_B)$ with $\mathbf{c}_2 = (c_R, c_C, c_B)$ or $\mathbf{p}_3 = (p_G, p_C, p_M)$ with $\mathbf{c}_3 = (c_G, c_C, c_M)$. The three stated possibilities of reproduction of the given final light, **f**, result in a different spectral distribution but in the same CIE XYZ stimulus of the reproduced final light.

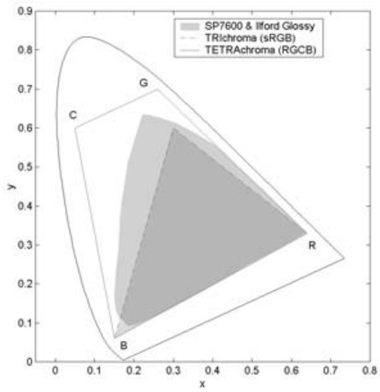
4. Discussion

So far it has been claimed that the color gamut of contemporary RGB scanning and display systems is too small to reproduce colors that are realizable e.g. by ink-jet printer. To prove this, color gamuts of such devices have to be compared. The color gamuts of contemporary RGB display systems, the proposed Tetra-chroma Display Unit, and the color gamut of the combination of Epson Stylus Pro 7600 ink-jet printer with UltraChrome inks and Ilford Glossy paper are marked in Fig. 6. It can be readily seen that cyans and orange-yellows that are achievable in printing are not reproducible by the contemporary trichromatic display systems. As referred earlier at the beginning of sec. 1, this leads into a poor function of soft-proofing.

In contrast to a conventional display, the proposed Tetra-chroma^3 Display Unit disposes color gamut through which the colors realizable on printing systems can be precisely reproduced.

5. Conclusion

The paper has introduced the additive-based multiprimary display unit including two color conversion methods. Such display unit disposes with two main strengths – it is able to reproduce metameric colors and has wider color gamut than contemporary not only additive-based display units but also subtractive systems such as ink-jet printing.



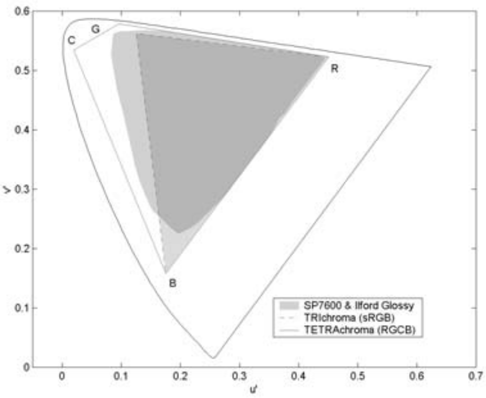


Fig. 6. Color gamuts of display and output systems in CIE xy (top) and CIE u'v' diagram (bottom).

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References

[1] KAISER J. *Kolorimetrie zdokonalených TV soustav*. Diploma, FEE CTU Prague, 2001. Supervised: E. Košťál, *IEEE Trans. Microwave Theory and Techniques,* 1994, vol. 42, no. 11, p. 2099 - 2106.

[2] BOLL, H. A color to colorant transformation for a seven ink process. In *Device Independent Color Imaging, SPIE Proceedings*, p. 108-18.

[3] FRASER, B., MURPHY, CH., BUNTING, F. *Real World Color Management.* Peachpit press, 2003, ISBN 0-201-77340-6.

[4] GRANGER, E. M. Press controls for extra-trinary printing. In *Proc. SPIE*, vol. 2658, 03/1996, p. 147-150.

[5] VIGGIANO, J. A. S., HOAGLAND, W. J. Colorant selection for six-color lithographic printing. In *Proc. IS&T/SID 1998 Color Imaging Conference,* p. 112-115.

[6] AJITO, T. et al. Color conversion method for multiprimary display using matrix switching. *Optical Review*, 2001, vol. 8, no. 3, p. 191-7.

[7] MURAKAMI et al. Color conversion method for multi-primary display for spectral color reproduction. *Journal of Electronic Imaging*, October 2004, vol. 13, no. 4, p. 701 – 708.

[8] PTÁČEK, M. *Přenosové soustavy barevné a digitální televize.* 2/E, Nadas Praha 1981, 488 p.

[9] SHARMA, G. *Digital Color Imaging Handbook.* CRC Press, 2003.

[10] KÖNIG, F., et al. A multiprimary display: Discounting observer metamerism. In *9th Congress of the International Color Association*, *Proc. SPIE*, 2002, vol. 4421.