Recent Progress with Extensions to CIECAM02

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Abstract

CIECAM02 has been used to predict colour appearance under a wide range of viewing conditions, to quantify colour differences, to provide a uniform colour space and to provide a profile connection space for colour management. However, several problems have been identified and this paper reports on the progress that has been made to improve and extend the CIECAM02 model to solve some of these problems.

Introduction

Since the recommendation of the CIECAM02 colour appearance model [1,2] by CIE TC8-01 Colour appearance modelling for colour management systems, it has been used to predict colour appearance under a wide range of viewing conditions, to specify colour appearance in terms of perceptual attributes, to quantify colour differences, to provide a uniform colour space and to provide a profile connection space for colour management. However, many problems have been identified and various approaches have been proposed to repair the model to enable it to be used in practical applications. During the 26th session of the CIE, held in Beijing in July 2007, a Technical Committee, TC8-11 CIECAM02 Mathematics, was formed to modify or extend the CIECAM02 model in order to satisfy the requirements of a wide range of industrial applications.

The main problems that have been identified can be summarised as follows:

1. Mathematical failure for certain colours;
2. The CIECAM02 colour domain is smaller than that of ICC profile connection space;
3. The HPE matrix;
4. The brightness function.

This paper reviews each problem in turn and then suggests a possible solution that either repairs the problem or extends the model.

Note that all notations used in this paper have the same meaning as those in CIE Publication 159 [1].

Mathematical Failure

It has been found that the Lightness function:

$$J = 100(A/A_w)^{cz} \qquad (1)$$

gives a problem for some colours. Here, c and $z = 1+\sqrt{Y_b/Y_W}$ are positive numbers and A and A_w which depend on the test sample and the illuminant, and are defined by

$$A = \left[2R'_a + G'_a + (1/20)B'_a - 0.305\right]\mathrm{N_{bb}} \qquad (2)$$

and

$$A_w = \left[2R'_{aw} + G'_{aw} + (1/20)B'_{aw} - 0.305\right]\mathrm{N_{bb}} \qquad (3)$$

respectively. Here, R'_a, G'_a, and B'_a, R'_{aw}, G'_{aw}, and B'_{aw} are the post-adaptation cone responses. Li and Luo [3] have shown that $A_w > 0$. However, it was found that A can be negative for certain samples [3-6]. In this case, a problem occurs when computing the Lightness attribute J.

It has been suggested that the source of the problem is the CAT02 transform which, for certain colours, predicts negative tristimulus values. Brill and Süsstrunk [4-6] found that the red and green CAT02 primaries lie outside the HPE triangle and called this as the 'Yellow-Blue' problem. They suggested this problem can be corrected by changing the CAT02 matrix defined by

$$M_{02} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix} \qquad (4)$$

to the M_{BS} matrix defined by

$$M_{BS} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0 & 0 & 1 \end{bmatrix}. \qquad (5)$$

It has been found that for certain colours, using matrix M_{BS} works well, but using matrix M_{02} does not. However, this repair seems neither to correct the failure of CAT02, nor the failure of CIECAM02. Another suggested repair [6] to CIECAM02 was to modify the values of R', G', B' by using:

$$R'' = \max(R',0), \quad G'' = \max(G',0), \quad B'' = \max(B',0) \qquad (6)$$

Thus, R'_a, G'_a, and B'_a are now defined by

$$R'_a = \frac{400(F_L R''/100)^{0.42}}{27.13 + (F_L R''/100)^{0.42}} + 0.1$$

$$G'_a = \frac{400(F_L G''/100)^{0.42}}{27.13 + (F_L G''/100)^{0.42}} + 0.1 \qquad (7)$$

$$B'_a = \frac{400(F_L B''/100)^{0.42}}{27.13 + (F_L B''/100)^{0.42}} + 0.1$$

respectively, and all will have values that are not less than 0.1. Hence, A as defined by equation (2) will always be non-negative and the J function (eq. (1)) is well defined.

The above approach is simple and the forward CIECAM02 now is well defined. However, there is a problem with the inverse model. That is to say, the values of XYZ predicted by the inverse CIECAM02 model may be different from the values of XYZ input to the forward CIECAM02 model under the exact same viewing conditions.

Li et al [7] developed a mathematical approach for searching the CAT02 matrix M. This approach combines the non-negativity constraint for the tristimulus values of the corresponding colours with the minimisation of the colour differences between the tristimulus values of the corresponding colours obtained by visual observations, and tristimulus values of the corresponding colours predicted by the model. This resulted in a constrained non-linear optimisation problem. A revised matrix has been derived and is given by

$$M_{cat}\begin{pmatrix} 1.007245 & 0.011136 & -0.018381 \\ -0.318061 & 1.314589 & 0.003471 \\ 0 & 0 & 1 \end{pmatrix} \tag{8}$$

The CAT02 matrix, together with several other matrices, was tested using 81 test illuminants and D65 as a reference illuminant. It was found that using the new CAT02 matrix gave the only combination which successfully predicted corresponding colours (without negative values) for all optimum colours and the CIE standard colorimetric observers. But, the accuracy for predicting the visual results is about one unit of CIELAB colour difference worse compared with the use of the original CAT02 matrix. Thus it seems that accuracy has to be sacrificed in order to ensure the non-negativity constraint for corresponding colours. However, one unit of CIELAB colour difference can be considered small compared with the likely observer variation in chromatic adaptation experiments.

This approach seems to solve the CAT02 failure problem. Unfortunately, it does not solve the mathematical failure for the CIECAM02. That is to say, there are colours located on or inside the CIE spectrum locus, which still cause the CIECAM02 problem with the J function (eq. (1)).

From the above discussions, if a constrained version of eq. (6) is introduced, a new problem occurs when inverting the CIECAM02 model. The approach of Li et al.[7] solves the CAT02 problem, but does not solve the CIECAM02 inversion problem. However, the two approaches can be further generalised and combined together to tackle this problem.

Firstly, the CAT02 matrix M should be chosen such that

$$R' \geq 0\,,\; G' \geq 0\,,\text{ and } B' \geq 0\,, \tag{9}$$

rather than using the constraint defined by eq. (6). Let,

$$p' = \begin{pmatrix} R' & G' & B' \end{pmatrix}^{\mathrm{T}} \text{ and } g = \begin{pmatrix} X & Y & Z \end{pmatrix}^{\mathrm{T}} \tag{10}$$

Here, the superscript T means the transpose of a vector or matrix. Thus, it follows from the computational steps of CIECAM02 [1,2], p' and g satisfy:

$$p' = M_{\mathrm{HPE}} M^{-1} \Lambda M g\,. \tag{11}$$

Here, M is the CAT02 matrix defined by eq. (2), M_{HPE} is the Hunt-Pointer-Estevez matrix defined by

$$M_{\mathrm{HPE}} = \begin{bmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.00000 & 0.00000 & 1.00000 \end{bmatrix}, \tag{12}$$

and Λ is a diagonal matrix depending on the test illuminant and the degree of adaptation and is given by

$$\Lambda(D) = \begin{pmatrix} D\dfrac{Y_w}{R_w} + 1 - D & & \\ & D\dfrac{Y_w}{G_w} + 1 - D & \\ & & D\dfrac{Y_w}{B_w} + 1 - D \end{pmatrix}, \tag{13}$$

Note that D is the degree of adaptation and has a value between zero and one. Full adaptation is represented when $D = 1$ and no adaptation when $D = 0$. Note also that

$$\Lambda(0) = \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}, \quad \Lambda(1) = \begin{pmatrix} \dfrac{Y_w}{R_w} & & \\ & \dfrac{Y_w}{G_w} & \\ & & \dfrac{Y_w}{B_w} \end{pmatrix}, \tag{14}$$

$$\Lambda(D) = D\Lambda(1) + (1 - D)\Lambda(0) \tag{15}$$

Thus, it follows from equations (11-15) that

$$\begin{aligned} p'(D) &= M_{\mathrm{HPE}} M^{-1}[D\Lambda(1) + (1-D)\Lambda(0)]Mg \\ &= DM_{\mathrm{HPE}} M^{-1}\Lambda(1)Mg + (1-D)M_{\mathrm{HPE}}g \end{aligned} \tag{16}$$

It can be shown that if the chromaticity of the input sample is located on or inside the CIE spectrum loci (1931 and 1964),

$$M_{\mathrm{HPE}}\, g \geq 0\,. \tag{17}$$

In fact, Figure 2 shows the CIE spectrum loci (1931, and 1964, dotted curves) and three straight lines. For any chromaticity located on or below the top line and on or above the two lower lines, inequality (17) holds. Figure 3 and Figure 4 show enlarged parts of Figure 2. All clearly show the inequality, eqn. (17), holds for any sample with chromaticity located on or inside the CIE spectrum loci.

Hence, it follows from equation (16) and inequality (17) that

$$p'(D) \geq 0\,,\text{ if } M_{\mathrm{HPE}} M^{-1}\Lambda(1)Mg \geq 0\,. \tag{18}$$

Next it is noted that for any positive number μ, $M_{\mathrm{HPE}} M^{-1}\Lambda(1)Mg \geq 0$ is equivalent to $M_{\mathrm{HPE}} M^{-1}\Lambda(1)M(\mu g) \geq 0$. Thus it is sufficient to consider the tristimulus vector g defined in terms of chromaticity coordinates, i.e.

$$g = \begin{pmatrix} x \\ y \\ z \end{pmatrix}, \text{ with } x + y + z = 1\,. \tag{19}$$

Let g_1 and g_2 be the two samples, their chromaticity coordinates (x, y) are shown in Figure 1 as crosses. Thus, any point g on the dotted line between g_1 and g_2 can be expressed as:

$$g = \sigma g_1 + \omega g_2\,,\text{ with } \sigma \geq 0\,,\; \omega \geq 0\,,\text{ and } \sigma + \omega = 1 \tag{20}$$

Now $M_{\mathrm{HPE}} M^{-1}\Lambda(1)Mg \geq 0$ for any point g on the dotted line in Figure 1 is equivalent to $M_{\mathrm{HPE}} M^{-1}\Lambda(1)Mg_1 \geq 0$ and $M_{\mathrm{HPE}} M^{-1}\Lambda(1)Mg_2 \geq 0$. Therefore, the matrix M should be chosen so that, for any point g on the CIE locus, the following inequality holds:

$$p' = M_{\mathrm{HPE}} M^{-1}\Lambda(1)Mg \geq 0 \tag{21}$$

Finally, the matrix M should be chosen to fit the experimental data well. All data sets used to derive and test CIECAM97s and/or CIECAM02 can be used. For details about each of the data sets, see reference [8] and further references in that paper.

For assessing the fit to the experimental data, the value of CV (coefficient of variation) is used. Note that the CV was used for measuring the performances of CIECAM97s [9] and CIECAM02 [8]. Let V_i and P_i, $i = 1,2,\cdots,n$, be the visual and model predicted results. The CV value measuring the closeness of the model prediction to the visual results is defined by:

$$CV = 100[\frac{1}{n}\sum_{i=1}^{n}(V_i - P_i)^2]^{1/2} / [\frac{1}{n}\sum_{i=1}^{n}V_i] \qquad (22)$$

The lower the CV value, the better the performance of the model. For example, CV=20 means there is a 20% difference between the visual results and model prediction.

Thus, the above discussions lead to a constraint and non-linear optimization problem. Besides, the problem depends on the illuminants used. The illuminants used for the optimization are: A, D50, D55, D65, D75, D90, F1-F11, white LED, and 5 high pressure discharge lamps defined in Table T.7 of CIE Pub 15:2004[18]. Computational work was carried on a personal computer using Matlab 7.0. It was found that with a different initial guess, the solutions (matrices) could be different, but the models have the same overall performance using the visual data sets [8] that were used in the development and testing of CIECAM97s and CIECAM02. For example, if the initial guess was chosen as the identity matrix, the final matrix obtained was the following:

$$M_{CAM} = \begin{pmatrix} 0.211720 & 0.837987 & -0.049707 \\ -0.65974 & 1.542704 & 0.117036 \\ 0 & 0 & 1 \end{pmatrix} \qquad (23)$$

It was also noted that no matter what initial guess was chosen, the third row of the output matrix is the same as the third row of the matrix defined by eq. (23).

The performance of the CIECAM02 with the original CAT02 matrix defined by eq. (4), the optimisation matrix defined by eq. (23) and the HPE matrix defined by eq. (12) was tested using all the visual data sets and the results in terms of CV values for the Lightness *(J)*, Colourfulness (*M*) and Hue Composition (H) attributes are listed in Table 1. This table, shows the CV values for the *J*, *M*, and *H* attributes with the original CAT02 (Ori), optimization (Opt) and HPE matrices under each of the data sets indicated in the first column. For example, the value 11.65 in row 6 and column 2 is the CV value for the Lightness using the original CAT02 matrix against the CRT data set. The value 18.36 in row 6 and column 6 is the CV value for the Colourfulness using the optimization matrix against the CRT data set. The values in the bottom row indicate the average performance for each of the attributes and each of the matrices across all the data sets. For example, the value 6.99 in the bottom row and last column is the mean CV value for the Hue Composition across all the data sets for CIECAM02 with the HPE matrix.

Comparing the optimisation matrix with the original CAT02 matrix, it can be seen from Table 1 that the CV values for each attribute with the optimization matrix can be slightly larger with certain data sets and smaller with others. The overall (mean) performance becomes slightly worse for the Lightness attribute, which is encouraging since with the optimization matrix, the mathematical failure for CIECAM02 is repaired under all the illuminants used for the optimisation for all the colours with chromaticity coordinates not outside the CIE chromaticity locus. Using the optimisation matrix gives overall performance for the Colourfulness and Hue Composition that is approximately the same as that obtained using the original CAT02 matrix.

Comparing the optimisation matrix with the HPE matrix, it can be seen from Table 1, that the overall performance with the optimisation matrix is slightly better than with the HPE matrix. But, with the optimization matrix, the mathematical failure is corrected with the illuminants used in the optimisation. However, with the HPE matrix, it is assured that there is no mathematical failure with all illuminants since the inequality (21) in this case becomes

$$p' = M_{\mathrm{HPE}} M^{-1} \Lambda(1) M g = \Lambda(1) M_{\mathrm{HPE}}\, g \geq 0 \qquad (24)$$

which is always true if the chromaticity of the input sample g is located on or inside the CIE spectrum loci. Thus, it may be better if the HPE matrix is chosen for the CAT02 matrix, which results in the simplification in the CIECAM02 model as well.

Table 1: Performance of CIECAM02 against each of the datasets using the CAT02 matrix (Ori), optimum matrix(Opt) and HPE matrix(HPE)

Group	J/Ori	J/Opt	J/HPE	M/Ori	M/Opt	M/HPE	H/Ori	H/Opt	H/HPE
RHL	10.64	10.92	10.94	17.79	18.08	17.94	6.88	6.68	6.92
RLL	11.35	11.67	11.7	18.56	18.94	18.84	7.08	6.85	7.16
RVL	13.31	13.44	13.46	18.39	18.96	18.92	6.53	6.53	6.52
RTE	14.85	14.78	14.76	23.67	23.39	24.76	7.07	6.93	7.14
CRT	11.65	11.69	11.69	19.61	18.36	19.51	6.74	7.04	7.59
M35	19.33	19.89	19.97	16.06	15.99	16.24	7.23	7.44	7.49
LTX	16.53	16.58	16.59	14.2	14.37	14.44	5.81	5.61	5.6
JUA	14.24	14.23	14.23	20.34	20.36	20.25	7.65	7.43	7.49
Mean	13.99	14.15	14.17	18.58	18.56	18.86	6.87	6.81	6.99

CIECAM02 domain is smaller than that of ICC profile connection space

The International Color Consortium (ICC) has developed and refined a comprehensive and rigorous system for colour management [10]. In an ICC colour management work flow, an input colour is mapped from a device colour space using an A2B (device dependent space to device independent space) tag to a profile connection space (PCS) and then through a B2A (device independent space to device dependent space) tag to the output device space. The tags are look-up tables. The processing information or image can be interpolated using the look-up tables.

In the ICC specification, the PCS is selected as either XYZ or Lab space under illuminant D50 and the 2° observer. The tag for

A2B contains the PCS values corresponding to the uniform sampled 3D grids in device space (for example, RGB). The tag for B2A contains the device values corresponding to the uniform sampled 3D grids in the PCS (or the selected space). For example, the 3D grids in Lab space are sampled with L* between 0 and 100, a* and b* between −128 and 127.

Generally speaking, the input and output devices have different gamuts and hence a gamut mapping is involved. Gamut mapping in XYZ space can cause problems because of the perceptual non-uniformity of that colour space. Lab space is not a good space for gamut mapping since lines of constant hue are not generally straight lines, especially in the blue region [11]. CIECAM02 has been shown to have a superior perceptual uniformity as well as better hue constancy [12]. Thus, the CIECAM02 space has been selected as the gamut mapping space.

However, the PCS tag grids can contain non-physical colours, which cause problems when transforming to CIECAM02 space, for example, in the Lightness function *J* defined in eq. (1) and the calculation of the parameter *t* defined by

$$t = \frac{(50000/13)N_c N_{cb} e_t \left(a^2 + b^2\right)^{1/2}}{R'_a + G'_a + (21/20)B'_a} \tag{24}$$

When computing J, the value of A can be negative and when computing t, $R'_a + G'_a + (21/20)B'_a$ can be at or near zero. One approach [13, 14] to solving these problems is to find the domain of CIECAM02 and to pre-clip or map colour values outside of this domain to fall inside or on this domain boundary, and then the CIECAM02 model can be applied without any problems. The drawbacks of this approach are that a two step transformation is not easily reversible to form a inverse solution and clipping in some other colour space would seem to defeat much of the purpose of choosing CIECAM02 as the gamut mapping space. Another approach [15] is to extend CIECAM02 so that it will not affect colours within its normal domain but it will still work, in the sense of being mathematically well-defined, for colours outside its normal domain. To investigate this, the J function eq. (1) and the non-linear post-adaptation functions (eq. (7)) were extended. Furthermore, scaling factors were introduced to avoid the difficulty in calculating the t value (eq. (24). Simulation results showed this extension of CIECAM02 works very well and full details can be found in the reference [15].

The HPE matrix;

Kuo et al [16] found that the sum of the first row of the HPE matrix (eq. (12)) is different from unity, which causes a non-zero value of a and b when transforming the test light source to the reference (equal-energy) light source under full adaptation. Hence a slight change to the matrix should be made. For example, the top right element −0.07868 could be changed to −0.07869. In fact, Kuo et al [16] suggested changing each element in the first row slightly.

The brightness function

The brightness function of CIECAM02 is different from the brightness function of the older CIECAM97s model. The major reason for the change [17] was because of the correction to the saturation function (*s*). However, it has been reported that the brightness prediction of CIECAM02 does not correlate well with the appropriate visual data. It might not be surprising that there is a problem with the brightness prediction since there is little relevant visual data available compared, for example, to data for the Lightness, Colourfulness and Hue attributes. Hence, more visual data is needed in order to improve the brightness prediction.

Conclusions

This paper has reviewed some of the problems with the CIECAM02 colour appearance model and reported progress towards repairing or extending the model. A mathematical approach has been proposed for extending the CIECAM02 colour domain in terms of chromaticity. The proposed approach led to a large scale constrained non-linear optimization problem and an optimisation matrix has been obtained. Hence, the mathematical failure of the CIECAM02 model for all illuminants used for the optimisation can be avoided for all the colours with chromaticity coordinates not outside the CIE chromaticity locus. However, the performance test has shown that the HPE matrix may be a better choice because it repairs the mathematical failure for any illuminants with only a slightly worse performance when fitting all the visual data sets used for developing and testing CIECAM97s and CIECAM02, compared with the optimisation matrix. In addition, the HPE matrix allows the CIECAM02 model to be further simplified.

References

[1] CIE (2004) A color appearance model for color management systems: CIECAM02, Publication 159: 2004, CIE Central Bureau, Vienna.

[2] Moroney N, Fairchild MD, Hunt RWG, Li CJ, Luo MR, Newman T, The CIECAM02 colour appearance models, Proceedings of the 10th of CIC, Scotsdale, USA, November, 2002, pages 23-27.

[3] Li CJ, Luo MR, Testing the robustness of CIECAM02, Color Res. Appl. 2005; 30: 99-106.

[4] Brill MH, Irregularity in CIECAM02 and its avoidance. Color Res. Appl. 2006; 31: 142-145.

[5] Süsstrunk S and Brill MH, The nesting instinct: Repairing non-nested gamuts in CIECAM02, Late-breaking-news paper at 14th SID/IS&T Color Imaging Conference, Nov. 2006.

[6] Michael H. Brill and Sabine Süsstrunk , Repairing Gamut Problems in CIECAM02: A Progress Report, Color Research and Application, Volume 33, Issue 5, Date: October 2008, Pages: 424-426.

[7] Li CJ, Perales E, Luo MR and Martínez-Verdú F, The Problem with CAT02 and Its Correction, submitted to Color Res. Appl, 2009.

[8] Li CJ, Luo MR, Hunt RWG, Moroney N, Fairchild MD and Newman T, The Performance of CIECAM02, CIC10, Scotsdale, USA.

[9] Luo MR and Hunt RWG, The structure of the CIE 1997 colour appearance model (CIECAM97s, Color Res. Appl., 23, 340-350, 1998.

[10] ISO 15076-1:2005, Image technology, colour management-Architecture, profile format and data structure-Part I: Based on ICC.1:2004-10, http://www.color.org.

[11] Moroney N, A hypothesis regarding the poor blue constancy of CIELAB, Color research and Application, 28(5), 371-378, 2003.

[12] Moroney N and Han Z, Field trials of the CIECAM02 colour appearance, CIE 25th Quadrennium, 2003.

[13] Tastl I, Bhachech M, Moroney N, and Holm J, ICC colour management and CIECAM02, Proceedings of the 13th of CIC, pages 217-223, 2005.

[14] Guay R and Shaw M, Dealing with imaginary color encodings in CIECAM02 in an ICC work flow, Proceedings of the 13th of CIC, page 318, 2005.

[15] Gill GW, A solution to CIECAM02 numerical and range issues, Proceedings of the 16th of CIC, 2008.

[16] Kuo CH, Zeise E, and Lai D, Robust CIECAM02 implementation and numerical experiment within an ICC workflow, Proceedings of the 14th of CIC, pages 215-219, 2006.

[17] Hunt RWG, Li CJ and Luo MR, Dynamic cone response functions for modes of colour appearance, Color Res. Appl., 28, 82-88, 2002.

[18] CIE (2004) Colorimetry, Publication 15: 2004, CIE Central Bureau, Vienna Vienna.

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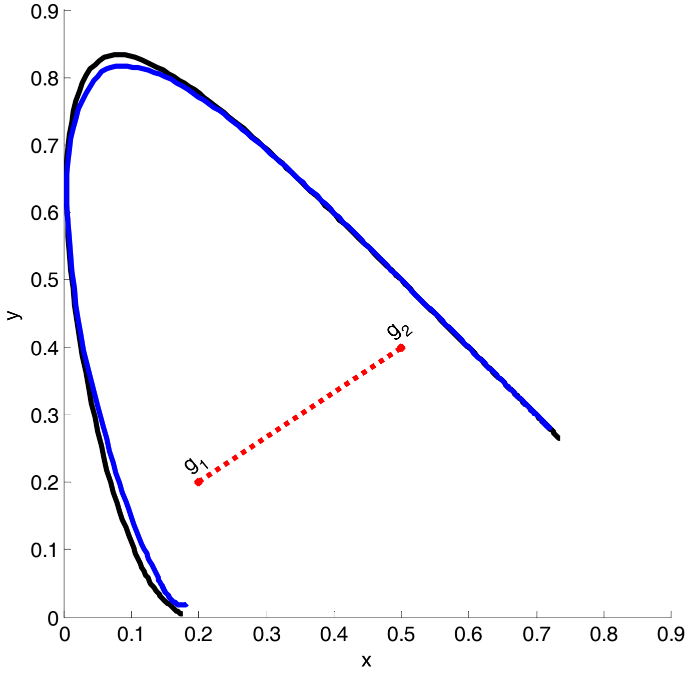

***Figure 1**: CIE spectrum loci*

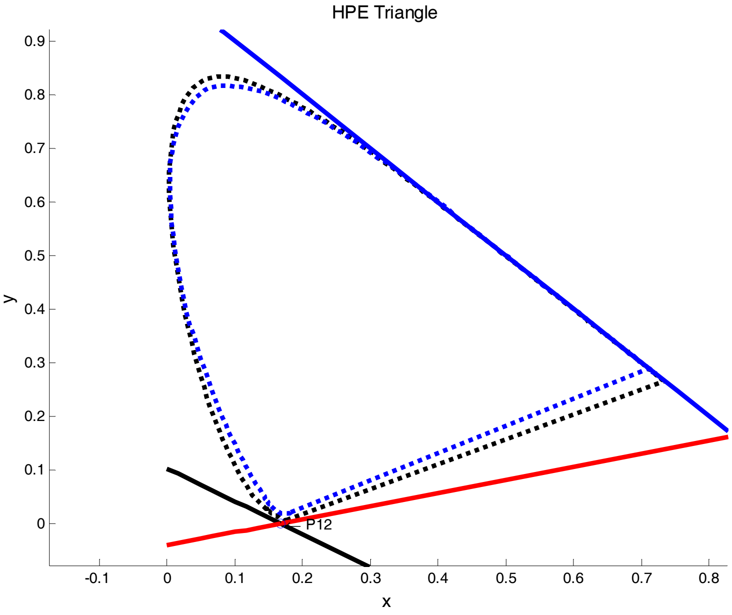

***Figure 2**: CIE spectrum loci (1931, 1964, Dotted curves); for any chromaticity located on or below the top line (blue) and on or above the two lower lines (red, black),* $M_{\mathrm{HPE}}g \ge 0$.

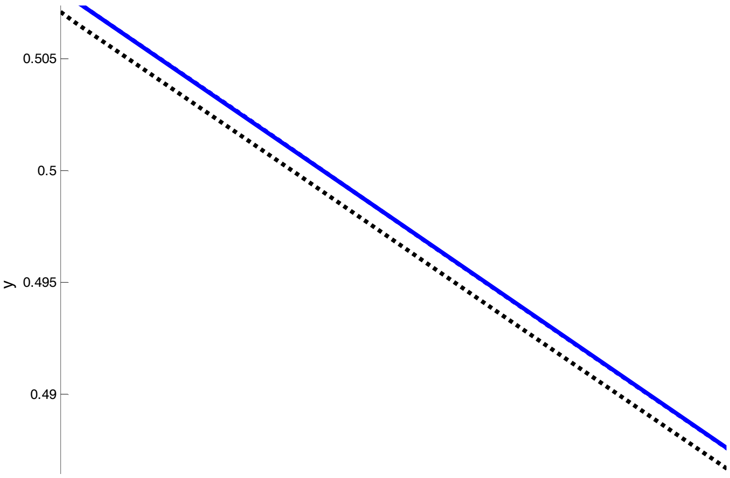

***Figure 3**: Enlarged part of Figure 2 along the top straight line*

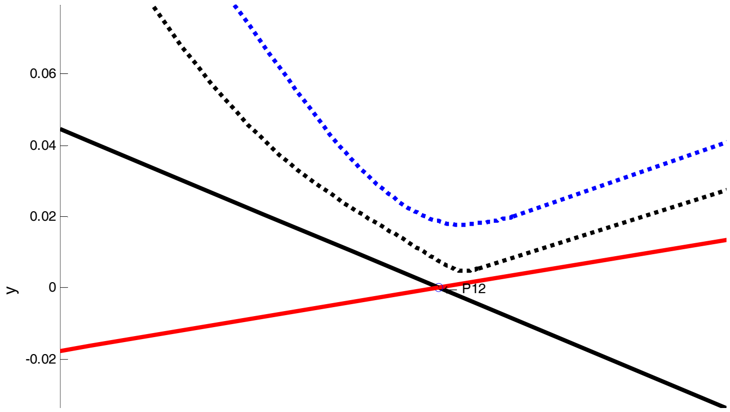

***Figure 4**: Enlarged part of Figure 2 along the bottom left corner*