Digital Coding of Color Video Signals—A Review

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(*Invited Paper*)

Abstract—**This paper reviews the field of the efficient coding of color television signals. Because this paper is perhaps the first review on this topic, some background is given in the areas of colorimetry, visual perception of color and color television systems. We assume that the reader has some familiarity with luminance encoding techniques.**

Coding techniques themselves are divided into two broad groups: component coding methods in which each component (usually three) is coded separately, and composite coding methods in which the composite television signal with its "color" modulated subcarrier is processed as a single entity. Both approaches are covered in detail.

The field is still growing, pushed primarily by the desire in the television area to find digital coding standards accepted by both broadcasters and carriers and suitable for use with NTSC, PAL and SECAM television systems. We discuss this aspect by comparing composite and component coding methods.

I. INTRODUCTION

THE digital coding of color video signals has received considerably less attention than the coding of monochrome video signals. However, given the current widespread proliferation of color television systems and the general preference for color pictures versus monochrome, it is obvious that the efficient coding of color picture signals is of prime importance. Broadcast color television systems make highly efficient use of the analog bandwidth to accommodate the increased information content of color signals. If the same relative efficiency is to be achieved in the encoding of color signals as has been achieved for monochrome, it is going to require a great amount of ingenuity.

The first attempt in digitally encoding a color signal most probably started in 1960 with the work of R. L. Carbrey [1] on applying PCM to a broadcast color television signal. A few papers were published on the subject during the following 11 years until 1971 when there was a marked increase which has persisted to the present and gives every indication of continuing. It therefore seems especially appropriate to review this field now while many new techniques are still being explored.

In laying the foundations of the present-day color television standards in the late 1940's, much study went into various background topics such as colorimetry and visual perception so as to match the resulting signal to the color fidelity requirements of the human observer. Further, additional studies have been made in the area of threshold color-difference perception and on the interaction between the "brightness" (luminance) and "color" (chrominance) components of the signal. To enable the reader to fully appreciate the various factors that bear on the encoding of color signals, we have gone into background material in some detail. Section II provides basic information in the area of colorimetry, laying a foundation for the colorimetric properties of color television. Section III describes the format of the three major color television systems in use in the world today, and some of the considerations that led to these standards. Section IV covers aspects of the work in color vision which bear on the problem of efficiently encoding color video signals. Final preparation for the coding sections is given in Section V where the statistical nature of color signals is described. Readers with familiarity in these background areas may wish to jump straight to Section VI although there is some work on color vision in Section IV that is perhaps not widely known to workers in the coding field.

We assume that the reader has some familiarity with basic waveform encoding techniques (see [2]). Coding of the luminance component per se will not be discussed in any detail. Of course, in coding the composite signal it is not feasible to divorce the coding of the luminance and chrominance components. Reviews of work on luminance encoding are available for readers who would like more background. Reference [3] covers the proceedings of a special conference on efficient picture coding, covering all aspects. References [4], [5] and [6] are special issues on signal processing which contain large sections describing video coding techniques.

From the first experiments in color encoding two somewhat separate approaches have been exploited. The first is to operate directly on the composite television signal, whereas the second divides the signal into three components, codes each component separately and then, after transmission, combines them again to form a composite signal. These two different approaches are examined in some detail in Sections VII and VI, respectively. Finally, in Section VIII we compare the implications of the composite and component encoding methods and conclude that, at least in the short- to medium-term future, both coding strategies will find important application.

We express a word of caution concerning the assessment of the performance of different encoding techniques. At the very minimum, such assessment requires the measurement of the bit-rate for a given picture quality. It is primarily the assessment of picture quality that is so variable. Picture quality depends on many factors, for example lighting conditions and monitor adjustments, the range of picture material that is presented, whether a single stored frame (or photograph) is being viewed, the amount and type of movement contained in the scene and the experience and expectations of the viewers.

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In the work on component coding described in Section VI, rates in the range of 1-2 bits/pel (picture element) have been found to give "good" quality pictures. But, in many cases, quality is based on single-frame simulations or on a small range of picture-material not representative of that handled by broadcast television. The situation will only be eased when all workers adhere to a common testing procedure (such as that recommended by the CCIR [7]) and use common picture material.

This difficulty in comparing picture quality, in turn, complicates the task of the authors in comparing different coding schemes. Even side-by-side comparison of picture quality would not provide definitive ratings since other factors such as error performance, cost, complexity and compatibility will all affect the final decision on the type of coder most suitable for a given application. Finally, the field of color coding is the subject of a great deal of current activity, and much of the research required to reach firm conclusions on the relative worth of various schemes has yet to be completed.

II. REPRESENTATION OF COLOR

A. Trichromacy

There is a long history associated with the science of color, and much of this history has been recently reported by MacAdam [8]. Those interested in the early work will also find an interesting collection of papers in a book by MacAdam [9] that spans a period of approximately 2000 years. The credit for the great advance in the science of color concerning the trichromacy of vision generally goes to Thomas Young for his advancement of the concept that the retina is composed of three sets of sensitive mechanisms—one for each of three principal colors [10]. Today it is generally accepted that there are three types of cones in the retina which mediate color vision at light levels greater than approximately 10 cd/m^2.

The natural counterpart to the trichromacy of vision is the trichromacy of color mixture. Maxwell studied color mixtures and demonstrated the first three-color projection in 1855, a description of which appears in the reprint of his 1857 paper [9]. Maxwell's work formed the basis for colorimetry—the technique of the measurement of color.

B. Colorimetry

Colorimetry is based on the premise that a relationship can be found between the physical stimuli and the visual sensation that arises from them. At the foundation of 3-color colorimetry lie a series of rules generally attributed to Grassman [11]. Two of the more important rules can be expressed as follows:

1. Any color stimulus can be matched (in appearance) by the additive mixture of three matching stimuli provided that no one of the three matching stimuli can be matched by the remaining two. This can be expressed as

$$(C) = \alpha(P_1) + \beta(P_2) + \gamma(P_3) \tag{1}$$

where (C) is a color that is matched by α units of color (P_1), β units of color (P_2), and γ units of color (P_3). The colors (P_1), (P_2) and (P_3) are conventionally called primaries.

2. The luminance[1] of a color mixture is equal to the sum of the luminances of the components in the mixture

$$L = L_1 + L_2 + L_3. \tag{2}$$

These rules have been extensively tested experimentally, and some discrepancies have been found (see Guth [12] for a review).

Wintringham [13] discusses the foundations of colorimetry in terms of a somewhat idealized set of experiments designed to determine what mixture of three primary colors would appear exactly like a spectral color. In these experiments an adjustable mixture of three well-chosen monochromatic lights act as the primaries. Subjects adjust the strengths of the three primaries to match each color in the series of spectral colors after first matching a white that has equal energy in all parts of the visible spectrum. The match to white represents one unit of each primary.

Note that we have not mentioned the absolute intensity or radiance of the spectral colors that are matched. This was intentional because the relative proportions of each of the three primaries is independent of the radiance over a wide range. Instead of referring directly to the number of units required to make the match, colorimetrists use normalized quantities called chromaticity coordinates expressed by the relations:

$$r = R/(R + G + B)$$

$$g = G/(R + G + B)$$

$$b = B/(R + G + B) \tag{3}$$

where we have changed the notation such that the units α, β and γ, which are called tristimulus values, have been replaced by the symbols R, G and B, respectively, to agree with the common usage of Red, Green and Blue primaries in these experiments. The results obtained by Guild [14] in his fundamental measurements of color mixture for 7 subjects are shown in Fig. 1.

The normalizing process we have just carried out to obtain the chromaticity coordinates has eliminated the radiance information, and we are left with only two pieces of information. The third dimension of color is obtained by a separate measurement of luminance. In a three-primary match to the reference white, the ratios of each of the three component luminances contributed by each primary to the total luminance are called the luminosity coefficients.

C. Color Transformations

A colorimetrist designates color by a graphical representation in a color space. This requires the data for a "Standard Observer" that would be representative of the mixture data of color normals. As noted in Fig. 1, Guild [14] had obtained

[1] Luminance is a quantity measured in a photometer. It is the photometric brightness of a uniform, small field.

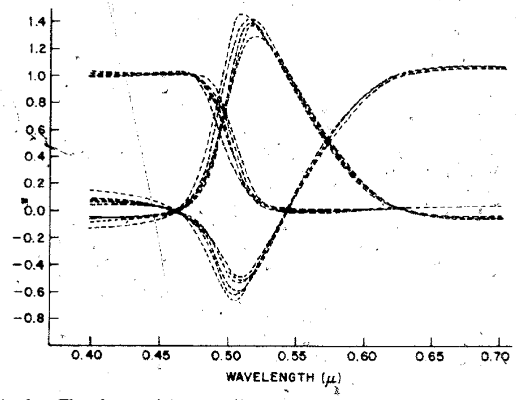

Fig. 1. The chromaticity coordinates versus wavelength of the spectral colors for seven observers using Guild's trichromatic colorimeter primaries, and the National Physical Laboratory (NPL) reference white (from Guild [14]).

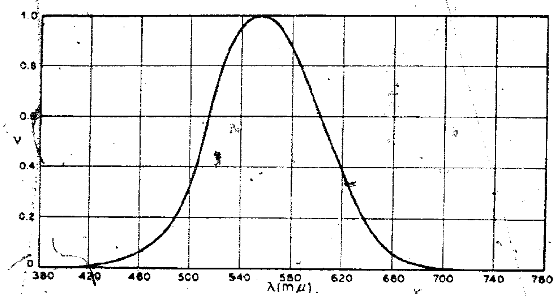

Fig. 2. Luminosity curve for the Standard Observer.[3] At 555 nm, one W is equivalent to 680 lumens (from Wintringham [13]).

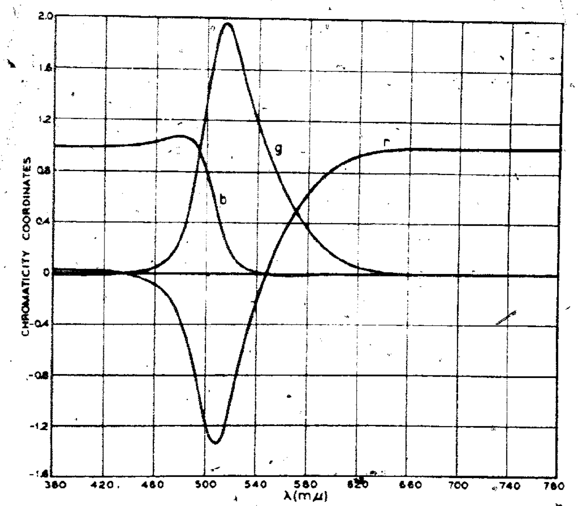

Fig. 3. Chromaticity coordinates of spectrum colors for the Standard Observer (from Wintringham [13]).[3] Primaries: 700.0 nm, 546.1 nm and 435.8 nm (NPL primaries). Reference white: equal-energy white.

data on 7 observers with a particular set of spectral primaries and a particular reference white. Wright [15] obtained data for 10 observers using different spectral primaries and did not normalize to the same white. In order to make use of the data of both Guild and Wright a transformation must be found between the tristimulus values of a color for two arbitrary sets of primaries. This has been solved by a number of workers for certain special cases. Wintringham [13] has treated the problem in a very general form in which the two reference whites are not the same. The result can be expressed in terms of a 3 × 3 matrix transformation.

D. *Chromaticity Diagrams*

The Commission International de L'Eclairage (CIE) in 1931 defined the color-matching data of the Standard Observer to be the mean of the data of Wright and Guild, and the equal-energy white was adopted as the reference white.[2] These specifications enable us to define the color mixture data of the Standard Observer (see, for example [13, 17]). The data indicate how much of each primary is needed to match spectral stimuli of equal radiance for the Standard Observer. The chromaticity coordinates of the spectral colors for the Standard Observer based on the National Physical Laboratory primaries are shown in Fig. 3. Corresponding tristimulus values for spectral stimuli of equal radiance are shown in Fig. 4. Chromaticity coordinates express fractions of a whole mixture. On the other hand, tristimulus values express how much of a primary is needed in a match to a given spectral color.

One form of graphical representation of this information on a chromaticity diagram using the r and g chromaticity coordinates is shown in Fig. 5. The spectral colors plot on the elongated horseshoe shaped curve called the spectral locus. The straight line connecting the two extremes of the spectral locus is called the line of purples. Note that the spectral locus extends outside the triangle formed by the three primaries which are, of course, located at (0,0), (0,1) and (1,0).

An important property of a chromaticity diagram concerns the calculation of the chromaticity of a mixture by a method analogous to a center of gravity system with the luminances of the components acting as weights. If two colors are additively mixed, then the chromaticity of the mixture lies on the straight line between the two chromaticities of the components. For a three-color mixture the chromaticity of the result lies within the triangle formed by the three component chromaticities. The extension of the spectral locus outside of the color triangle formed by the three primaries in Fig. 5 is a consequence of the necessity of adding one of the primaries to some of the spectral colors in order to carry out the match (equivalent to moving one of the terms from the right side of (1) to the left).

Suppose we wish to calculate the chromaticity of an object

[2] The CIE [16] had already adopted a standard relative luminous efficiency function V_λ shown in Fig. 2 for photopic ("normal daylight vision") conditions. The function represents the results derived from several different photometric methods of equating the brightness of spectral energy sources.

[3] The symbol "mμ" on the axis is outdated and has been replaced by "nm" in our text.

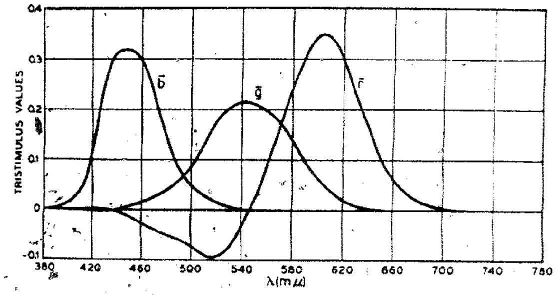

Fig. 4. Tristimulus values $\bar{r}$, $\bar{g}$ and $\bar{b}$ of spectral stimuli of equal radiance for the Standard Observer (from Wintringham [13]).[3]

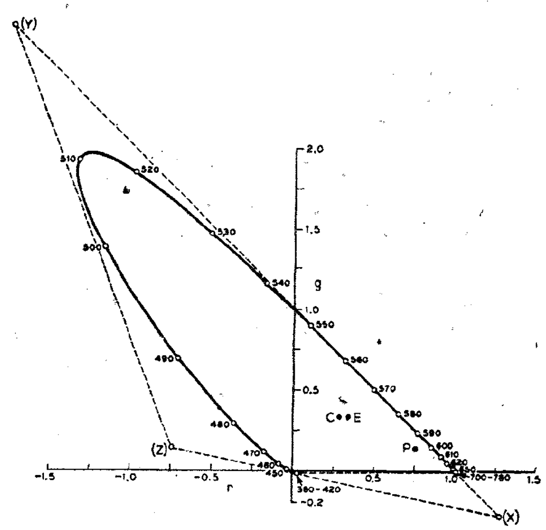

Fig. 5. The *rg* chromaticity diagram for the Standard Observer (from Wintringham [13]). The wavelengths (in nm) of the spectral colors appear on the horseshoe shaped locus. Point *E* represents equal-energy white, *C* represents Illuminant *C* which is a standard bluish-white source, *P* represents a specific color sample irradiated by Illuminant *C* and (*X*), (*Y*) and (*Z*) are the standard CIE nonphysical primaries discussed in Section II. D.

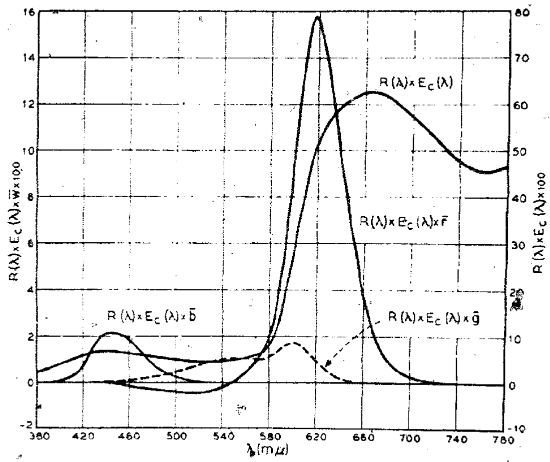

Fig. 6. Products of the tristimulus curves $\bar{r}$, $\bar{g}$ and $\bar{b}$ with the reflectance of a color sample, $R(\lambda)$, irradiated by Illuminant C, $E_c(\lambda)$ (from Wintringham [13]).[3]

that is illuminated by a light of a specific spectral distribution. The spectral distribution of the reflected light may, of course, be thought of as being composed of an infinite series of spectral colors. To determine how much of each primary is needed in the mixture, a product is formed of each of the tristimulus values with the spectral reflectance of the object as shown in Fig. 6. The areas under each curve, as obtained by integration, are the desired tristimulus values *R*, *G* and *B* for the sample. Chromaticity coordinates can be calculated using (3) and the point "*P*" is plotted in Fig. 5.

In 1931 such calculations were commonly performed on desk calculators, and the negative lobes of the functions of Fig. 4 introduce negative product terms in which the negative sign is error prone with repetitive summing and differencing operations. It would be much better if there were no negative lobes, and it would be convenient if the quantities were zero over as large a range as possible. Calculation of the luminance of a color would be made much easier if the luminosity coefficients of two of the primaries were equal to zero. The luminance of a color would then be equal to the number of units of the other primary used in the match.

It was these considerations, among others, that led the CIE to propose a new set of primaries. The spectral locus is totally contained within the triangle formed by these new primaries denoted by (*X*), (*Y*) and (*Z*) (as can be seen in Fig. 5) implying that all spectral colors can be matched with a positive quantity of each primary. The use of such "nonphysical" primaries should be no cause for concern. For measurement purposes any real set can be used and the results can be transformed by a 3 × 3 matrix to the nonphysical set.

Luminosity information is obtained from the tristimulus value of the (*Y*) primary—the luminosity coefficients of the other two primaries are equal to zero. The resulting tristimulus values $\bar{x}$, $\bar{y}$ and $\bar{z}$ are shown in Fig. 7. Note the all-positive nature of the functions, and that $\bar{y}$ is identical to the V_λ curve of Fig. 2. The *xy* chromaticity diagram for the 1931 CIE Standard Observer is shown in Fig. 8. The equal-energy white (*E*) has the coordinates (1/3, 1/3) because it is the reference white for this system. All the color mixture properties that we have previously described for the *rg* diagram are valid for this diagram, however, the equations for color mixture are especially simple for this case. If we are given the chromaticities x_1, y_1, x_2; y_2 and their luminances L_1 and L_2 the chromaticity of the mixture is simply

$$x_3 = \frac{x_1(L_1/y_1) + x_2(L_2/y_2)}{(L_1/y_1) + (L_2/y_2)}$$

$$y_3 = \frac{L_1 + L_2}{(L_1/y_1) + (L_2/y_2)} \qquad (4)$$

and the luminance is

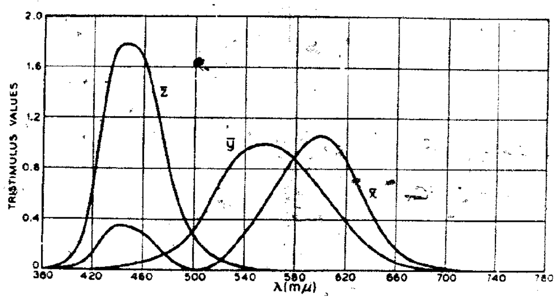

Fig. 7. Tristimulus values $\bar{x}$, $\bar{y}$ and $\bar{z}$ of spectral stimuli of equal radiance for the Standard Observer (from Wintringham [13]).[3]

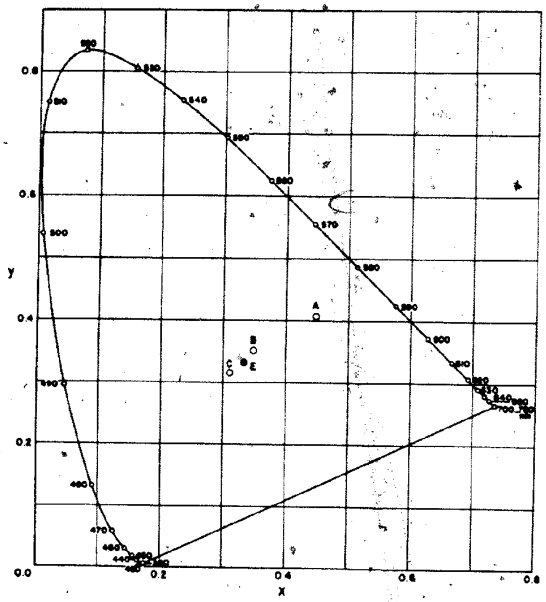

Fig. 8. 1931 CIE *xy* chromaticity diagram containing the spectral locus, line of purples, and the chromaticity locations *A*, *B*, *C* and *E* for CIE standard Illuminants *A*, *B*, *C* and equal-energy white (from Wyszecki and Stiles, Fig. 3.10 [17]).

$$L_3 = L_1 + L_2. \quad (5)$$

The 1931 Standard Observer was based on color matches using a 2° field. In 1964, the CIE defined another Standard Observer, but based on a 10° field. The data base was obtained from Stiles and Burch [18] and Speranskaya [19]. The location of certain wavelengths are somewhat shifted along the spectral locus in the 1964 $x_{10}y_{10}$ diagram as compared to the 1931 *xy* diagram as can be seen by examining Fig. 2.17 of [20].

It is important to realize that the chromaticity diagrams we have discussed pertain to color in the objective sense. They are based on color matches and not on color appearance. Information concerning the subjective color sensations of hue and saturation are not obtainable from a chromaticity diagram.

E. Uniform Chromaticity Diagrams

The *xy* chromaticity diagram is still in wide use today, but it has a major shortcoming for some practical applications. Color samples which have chromaticities which are equally distant from each other on the diagram are not equally different in appearance. MacAdam has determined the loci of chromaticities that are equally noticeably different from each of 25 representative colors for a constant level of luminance [21, 22]. Such loci are ellipses and they are shown on the *xy* diagram in Fig. 9. Notice how the differences vary over the diagram.

There have been many attempts to make a diagram in which equal distances correspond to equal differences in perception under the restriction that it be obtained by a linear transformation of the *xy* diagram [17].[4] However, the goal is impossible to attain strictly although improvements can be made. The 1960 CIE-UCS diagram [23] is one such diagram, and it is shown in Fig. 10 with a plot of MacAdam's ellipses. These ellipses tend to be more circular than those shown in Fig. 9. The transformation from *x, y* to *u, v* is as follows:

$$u = 4x/(-2x + 12y + 3)$$

$$v = 6y/(-2x + 12y + 3). \quad (6)$$

III. THE COLOR TELEVISION SIGNAL

A. Relation to Colorimetry

We can draw an analogy between a color television system and a colorimeter. The three phosphors of the receiver correspond to the three primaries of the colorimeter, and the camera taking filters correspond to the color mixture curves for these primaries. Each color in the scene before the camera must be matched by suitably controlling the light output of the receiver phosphors. This goal will be achieved if the light contributions from the receiver phosphors are adjusted to be equal to the tristimulus values appropriate to this sytem of primaries for each of the colors in the original scene. If we assume for the moment that the television system is linear, then the three signals from the camera should be proportional to these tristimulus values. As can be surmised from Section II, this is achieved by making the spectral sensitivity of the color filter in each of the three channels in the camera proportional to the corresponding color mixture curve of the Standard Observer for the receiver primary it controls. These relations were applied in the design of color television systems.

B. Format of the National Television System Committee (NTSC) Color Television Signal

The NTSC color television standards meet two basic requirements: (1) compatibility with existing monochrome receivers and (2) bandwidth containment of the color signal within the existing bandwidth for monochrome television.

[4] The latter condition is needed in order to retain the facility to carry out color mixture on the diagram by the method analogous to center of gravity systems.

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