ENGINEERING TRAINING SUPPLEMENT

No. 14

COLORIMETRY

BRITISH BROADCASTING CORPORATION

ENGINEERING TRAINING SUPPLEMENT

No. 14

COLORIMETRY

by

H. Henderson, B.Sc., A.M.I.E.E.
Head of Fundamentals Section, Engineering Training Department

BRITISH BROADCASTING CORPORATION

First published: July 1964

Published by

Technical Publications Section
British Broadcasting Corporation
London

Printed by

Smith & Ouzman Limited
London & Eastbourne

PREFACE

The object of this training supplement is to explain the basic principles of colorimetry in such a way that the electronic engineer with no previous knowledge of the subject can reach a sufficient standard to be able to go on, with understanding, to a study of the systems of colour television. The supplement is intended to be self-contained, but references to other publications are included as a guide to further reading. It is hoped that a further supplement will be issued, to cover circuit techniques associated with particular transmission standards, but at the time of writing (1964) no system has been adopted by the U.K. or the E.B.U. Whatever system is finally employed however, the basic principles of colorimetry will continue to apply.

ACKNOWLEDGMENTS

The BBC acknowledges its thanks to the Editor of *Contemporary Physics* for permission to reproduce the following three diagrams from the article *Interference Filters* by H. Henderson published in the August 1960 issue:

Fig. 4.4 Construction of a dichroic mirror
Fig. 4.5 Transmission characteristics of dichroic mirrors
Fig. 4.6 Optical system of a colour television camera

Thanks are also due to Hilger and Watts Ltd. for permission to reproduce Fig. 5.3 from *The Measurement of Colour* by Dr. W. D. Wright.

CONTENTS

1

PHOTOMETRY

Introduction

This chapter is devoted to the basic ideas of photometry, important in the first instance to monochrome television. In establishing the vocabulary necessary to the study of photometry and colorimetry the logical development of the subject may occasionally be impeded.

As in the study of sound, all light measurements made with instruments must finally agree with the magnitude of the sensation produced in the observer. This requirement imposes difficult restrictions for one may ask who is the observer and how is the magnitude of his sensations to be measured? In fact, no two real observers react in precisely the same way to light stimuli, and it has been necessary to postulate a standard or average observer whose responses have been determined by averaging the responses of large numbers of individual observers.

Visible Spectrum

The measurement of light (photometry) involves an attempt to reach a quantitative assessment of the sensation produced in the eye by the narrow region of the electromagnetic spectrum to which that organ is sensitive. This region (the spectrum) extends from wavelengths of about 400×10^{-9}m, i.e. 400 nm (blue), to 750 nm (red).* The eye is not equally sensitive over the whole of this region; it has maximum sensitivity to wavelengths in the centre of the spectrum, corresponding to yellow, which incidentally corresponds to the wavelengths carrying maximum energy in the sun's radiation. The curve of Fig. 1.1 relates eye sensitivity with wavelength for an average observer. If a photovoltaic cell is fitted with a filter such that the photoelectric current plotted against wavelength has the same shape as the response curve of the eye, a measuring instrument is obtained which is capable of calibration and more convenient to deal with than 'the average eye.'

The shape of the eye response curve does not vary significantly with change in the intensity level of the light observed (by contrast the frequency response of the ear varies considerably with change in incident sound level). At low light level there is some increase in sensitivity at the blue end of the spectrum (Purkinje effect) but this effect is unlikely to have significance in colour television.

*Wavelengths are sometimes quoted in Ångström units (10^{-10}metre) and sometimes in millimicrons (10^{-9}m). The millimicron is alternatively known as the *nanometre*, abbreviated to nm, and this is the unit used for expressing wavelengths in this supplement.

To calibrate the type of instrument just described a standard light-emitting source is required. Up to 1948 the fundamental source was a *standard candle* and there were many secondary sources which were rather easier to set up. In 1948 a new standard was introduced and has been internationally accepted. The new light source is a square centimetre of full radiator at the temperature of melting platinum and this is defined as having a light-emitting power of 60 *candelas*. The candela can usually be taken as having the same light-emitting power as the original standard candle. For most readers the old standard candle has a somewhat greater reality than 1/60 of a square centimetre of full radiator at a particular temperature, and the calibration of the light meter can be carried out in terms of standard candles. Of course light is not emitted

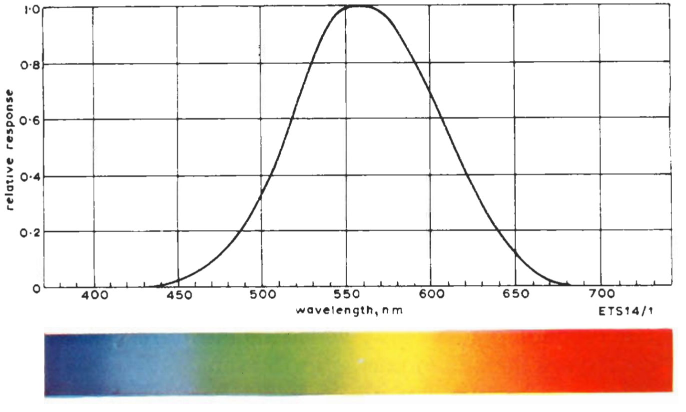


Fig. 1.1 Colour spectrum and spectral sensitivity curve of average eye

uniformly in all directions by a candle and 1 candle power (or candela) is defined as the light-emitting power of a standard candle in a horizontal direction. The flow of radiant energy from the candle is referred to as *luminous flux* which means simply light flow. Luminous flux is measured in *lumens* and the lumen is defined as the rate at which radiant energy falls upon a surface 1 square foot in area situated 1 foot from a source of 1 candle power. It follows that if the light-sensitive surface of the photovoltaic cell, with the eye-response filter and having a suitably-sensitive meter, is placed one foot from a standard candle (in a horizontal direction) then the number of lumens falling on its surface can be calculated from the area of the photocell and the meter can be calibrated in lumens.

Inverse Square Law

If the standard candle is regarded as a point source of light, luminous flux spreads out radially from it and if the light meter is moved from one foot to two feet from the source, the radiant energy falling on its light-sensitive surface falls to a quarter of the initial value. By placing the meter at various distances from the source it is possible to calculate the luminous flux received at each position and thus to calibrate the meter scale. The law employed in this calibration is the Inverse Square Law.

Illumination

We have more than once used the phrase *the number of lumens falling on its surface*. This phrase defines the term *illumination* which is usually measured in lumens per square foot of receiving surface. This unit was formerly known as the foot-candle but this is now deprecated.

The inverse square law relates the illumination of a surface (E) to the luminous intensity (I) in candelas (or candlepower) of the light source and the distance d between them.

$$E = \frac{I}{d^2}$$

If the surface does not receive the light perpendicularly (that is, normal to its surface) then the angle of obliquity θ is introduced and we have

$$E = \frac{I \cos \theta}{d^2}$$

where θ is the angle between the light rays and the perpendicular or normal to the surface.

Luminance

The light which falls upon a surface and illuminates it is absorbed, reflected or transmitted through it but in television only the light which is reflected from the illuminated surfaces and finally is responsible for the production of an image on the camera photocathode is of importance. Surfaces differ widely not only in the amount of light absorbed or reflected but in the way they reflect light. Two main classes of reflectors exist; the specular or mirror-like reflector and the diffuse reflector. We are concerned only with the second type. The perfectly-diffusing (or Lambert) surface is defined as one which reflects all the incident light and looks equally luminous (bright) in all directions. Deep virgin snow is a very good approximation to a Lambert surface. In the laboratory a freshly-scraped block of magnesium carbonate is employed.

A further term requires definition at this point. It is the *reflectance* (USA) or *reflection factor* ρ and is simply the ratio of the number of lumens reflected from a surface to the number falling upon it. For the skin on the forehead of a European the reflection factor is about 0·3.

An illuminated surface behaves as an extended source of light (i.e. as distinct from a point source) and its light-emitting power is sometimes expressed in candelas per square foot. The accepted unit of luminance (or brightness) is the foot-lambert and the luminance of a surface in foot-lamberts (L) is simply related to the illumination of the surface (E) in lumens per square foot by

$$L = \rho E$$

If therefore the forehead is illuminated at a level of 100 lumens/sq ft the luminance is 30 ft lamberts ($\rho = 0{\cdot}3$).

The mechanism of diffuse reflection requires the incident light to enter the reflecting surface (e.g. snow crystals) and be reflected many times within it before emerging in a direction quite unrelated to that of the incident light. If the diffusing surface is pigmented then absorption of light of certain wavelengths occurs during these internal reflections and the remaining light emerges and gives the surface its colour.

Image Illumination

In television, objects are so illuminated that some of the light diffusely reflected from them can be picked up by a lens system and used to form an image on a photocathode of a television camera tube. The image illumination at any point on the photocathode determines the magnitude of the electric signal produced at that point. It is necessary therefore to relate the luminance of an object (L) to the illumination of its image (E_1) formed on the photocathode. The relationship is

$$E_1 = \frac{\tau L}{4N^2} \quad \text{lumens/sq ft}$$

where τ is the transmission factor of the lens system defined by

$$\tau = \frac{\text{light leaving the lens to form the image,}}{\text{light entering the lens from the object}}$$

$L =$ object luminance in foot-lamberts and

$N =$ f number, i.e. the ratio of focal length of the lens to its effective diameter (f/d).

The iris controls the effective diameter of the lens and iris movement is calibrated in f numbers or stop numbers. Typical values are 2, 2·8, 4, 5·6, 8 etc., and the ratio between successive numbers is $\sqrt{2}$. 'Opening up by one stop' means increasing the iris diameter so that the f number changes from say f/4 to f/2·8. The image illumination doubles because E_1 is proportional to $1/N^2$ as shown in the above expression.

Consider as an example the image illumination of the forehead referred to previously which is formed on a photocathode by a lens set at f/4 when the luminance of the forehead is 30 foot-lamberts (as before).

$$E_1 = \frac{30}{4 \times 16} = \frac{30}{64} \text{ lumen/sq ft}$$

if τ is taken as unity. The image illumination at this point on the photocathode is about 0·5 lumen/sq ft and knowing the sensitivity of the camera tube the electrical output could be predicted.

Neutral Density Filter

The aperture of the lens controlled by the iris determines not only the image illumination but also the depth of field. When a lens is stopped down (the f number increased) the depth of field increases. If this is artistically undesirable, then a neutral density filter is introduced into the light path to reduce the image illumination. Such a filter must attenuate all the wavelengths of the visible spectrum to the same extent and appears a grey colour.

2

COLOUR VISION

Introduction

In this chapter the three-colour theory of colour vision is described and used to explain the effects of additive and subtractive colour mixing.

Visible Spectrum

When a narrow pencil of white light passes through a prism, light of the longer wavelengths is bent to a smaller extent than that of shorter wavelengths. The emergent beam is thus spread out and if allowed to fall upon a screen produces the familiar spectrum. As the eye scans the spectrum from one end to the other, it observes a change of colour from blue through green, yellow and orange to red. In the spectrum there are in fact about one hundred just noticeably different colours.

Colour Vision

It might be assumed from the information given in the previous paragraph that the eye possesses something like one hundred receptors, each capable of detecting a narrow spectral band, but a much simpler theory which assumes only three types of receptor accounts for most of the observed facts of colour vision. Only two types of light-sensitive nerve endings have been identified in the retina of the eye and these are known because of their shapes as *rods* and *cones*. The cones are most thickly clustered in a small central area on the retina which is most used in normal vision. Cones are associated with normal vision at ordinary levels of illumination and are clearly concerned with colour vision. The rods are scattered over the rest of the retina and seem to play no part in colour vision; they are more sensitive than cones at very low levels of illumination. So far three cone-type colour receptors have not yet been positively identified but their existence is assumed in the three-colour-receptor theory described below.

Three-colour Theory

The theory suggests that in the central area of the retina which is the only region of full colour vision there are cones capable of detecting the blue end of the spectrum, the red end of the spectrum and the central green region of the spectrum. The curves of Fig. 2.1 suggest possible spectral sensitivities of such receptors. Except at the red end of the spectrum the three response curves overlap to a considerable extent and light of a single spectral colour excites at least two of the eye receptors. The distinction between one colour and another must therefore be due to the relative excitation of these three receptors. At the red end of the spectrum only one receptor is stimulated and a considerable band of wavelengths exists which produce the same sensation of red. The eye sensitivity curve of Fig. 1.1 is obtained by summing the receptor responses at each wavelength.

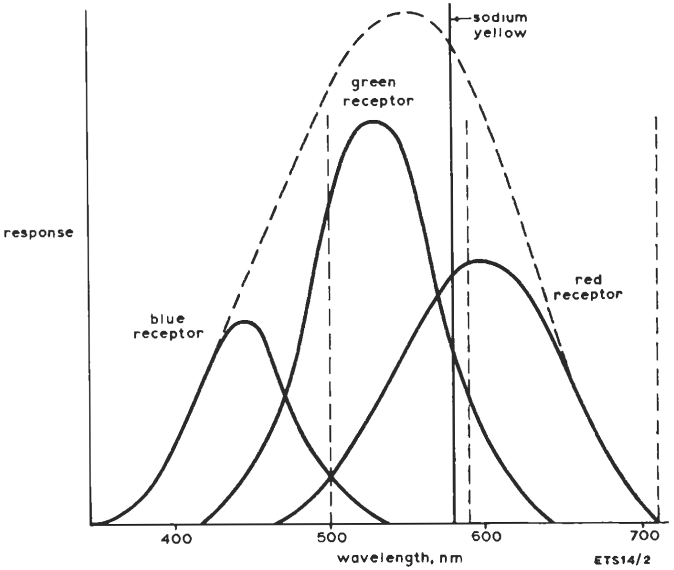


Fig. 2.1 Possible spectral sensitivities of eye receptors

Additive Colour Matching

The three colour receptors postulated above can be stimulated by narrow bands of radiation from the blue, green and red ends of the spectrum so that any spectrum colour or combination of spectrum colours can be matched as judged by the eye by suitably adjusting the relative stimulations of the three receptors. For example Fig. 2.1 shows that monochromatic yellow excites both green and red receptors: hence a suitable combination of red and green light will achieve the same result. The addition of red light and green light to give yellow light is one of the more striking demonstrations of colour matching.

Spectroscopically the two yellow lights are very different and the two can easily be distinguished by use of a narrow-band red or green filter. The monochromatic beam cannot pass through the red or the green filter. In the beam consisting of a mixture of red and green lights, the red light passes through the red filter whilst green light passes through the green filter.

The quantitative effects of three-colour matching can be represented by a triangle, as shown in Fig. 2.2. The primary colours red, green and blue are shown at the corners of the triangle. Mixtures of any two lie on the line joining them: thus yellow is shown half way between red and green, magenta halfway between red and blue, and cyan halfway between blue and green. A suitable mixture of green and magenta gives white as does a mixture of blue and yellow, or a mixture of red and cyan. These pairs of colours are called *complementary colours:* such colours are defined as any two which in suitable mixture match white. White is located at the centre of gravity of the triangle.

Subtractive Colour Matching

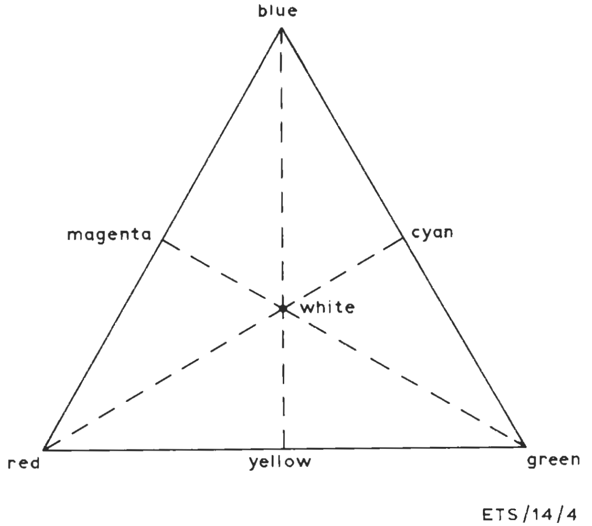
There is another method of colour matching known as subtractive colour matching and an account of this is given below because it is important in mixing coloured paints and in the use of colour filters.

A pigment present in a paint or a filter absorbs part of the incident light and appears coloured by virtue of the residue of the light it reflects or allows to be transmitted. Thus a magenta filter absorbs the green in white light falling upon it and transmits red and blue to produce magenta. Similarly a yellow filter absorbs the blue in white light and transmits red and green to produce yellow. A magenta filter is sometimes referred to as minus green (i.e. white minus green), a yellow filter as minus blue and a cyan filter as minus red. When three such filters are placed together no light can penetrate all three, because the first (magenta) absorbs the green, the second (yellow) absorbs blue and the third (cyan) absorbs red. The triangle of Fig. 2.3 shows pictorially the operation of subtractive colour mixing outlined above.

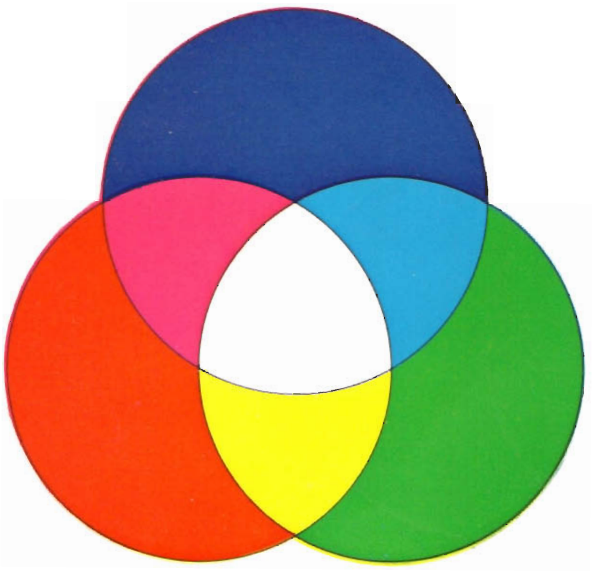
Spectral Reflection Characteristic of Coloured Surfaces

As mentioned above a pigmented surface appears coloured because of the wavelengths of the light it reflects, but for the pigment to achieve its characteristic absorption the light must penetrate the pigmented layer. After a number of reflections amongst the pigment granules the light emerges and leaves the surface in random directions. The directions of the emergent light thus bear little relation to the direction of the incident light; this is another example of the diffuse reflection mentioned in chapter 1.

Light is also reflected at the surface of the pigmented layer but this reflected light is not coloured because it has not suffered absorption by the pigment. If the incident light is white, the reflected light is also white and it mixes with and dilutes the coloured light diffusely reflected from the deeper pigment layer. When the pigmented surface is smooth, e.g. coated with a gloss enamel paint,



(a)



(b)

Fig. 2.2 Additive colour matching

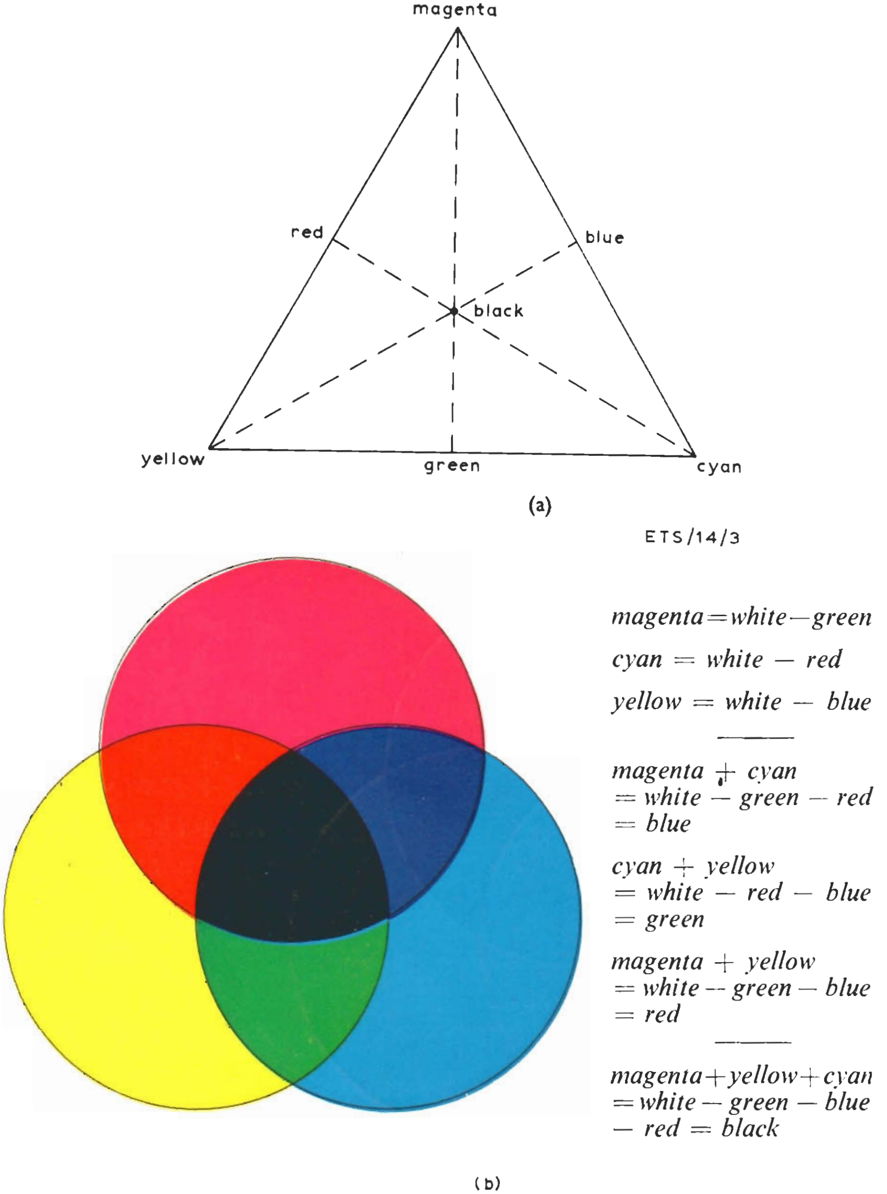


Fig. 2.3 Subtractive colour matching

a mirror-like (specular) reflection of white light takes place whilst with a matt surface the white light is diffusely reflected. Thus as shown in Figs. 2.4(a) and (b) matt surfaces appear to have more dilute colours than glossy surfaces

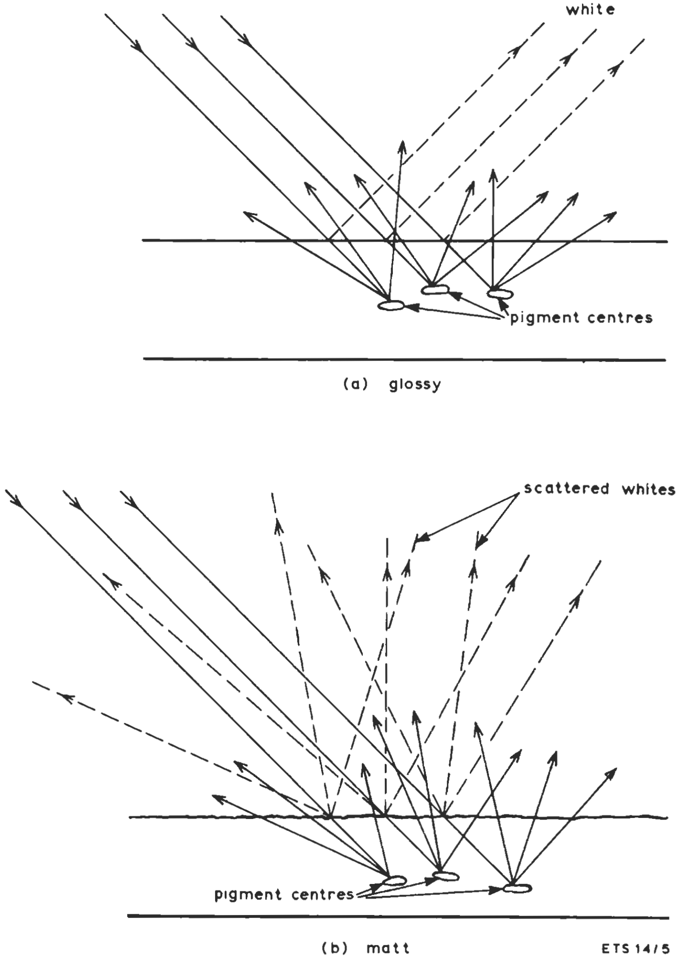


Fig. 2.4 Reflection of light from (a) gloss and (b) matt coloured surfaces

because for a glossy surface incident white light is reflected in a single direction and does not dilute the light diffusely reflected from the pigmented layer. However if a glossy surface is illuminated not by a beam of white light from a single direction but by an extended source then dilution or desaturation of the pigment colour occurs.

To avoid difficulties associated with the nature of the surface reflection, the spectral reflection characteristic of a coloured surface is determined as follows. The surface is illuminated by a narrow spectrum-band as a parallel beam falling at an angle of incidence of 45° as shown in Fig. 2.5 and the light reflected normally falls on a photocell to produce a galvanometer deflection. A standard white surface is first presented to the instrument and the sensitivity of the galvanometer adjusted to give a reading of 100%. The coloured surface then replaces the white surface and the percentage reflection of this surface for the particular narrow-spectrum band is given by the meter reading. By successively changing the colour of the incident beam from the blue to the

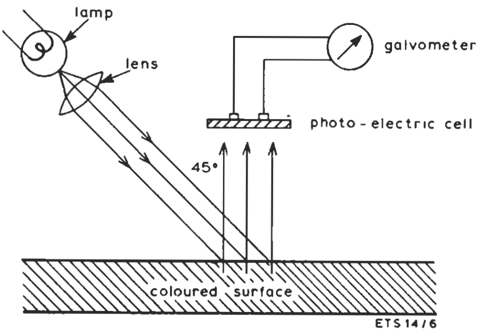


Fig. 2.5 Determination of the spectral reflection characteristic of a coloured surface

red end of the spectrum and at each colour relating the surface reflection factor to a standard white surface the spectral reflection characteristic of the surface can be plotted. Fig. 2.6 shows examples of such characteristics for a range of coloured surfaces. Examination of these curves supports earlier statements made about subtractive mixing. For example the yellow surface clearly reflects all the incident light except for the blue which it absorbs. Because blue contributes little to brightness a yellow surface is almost as bright as a white surface. The spectral reflection characteristic of the pastel pink surface shows an increased reflection of light at the red end of the spectrum superimposed on a significant reflection over the whole spectrum. Pink consists then of a mixture of red and white.

Sources of Light

A coloured surface cannot be said to possess a particular colour unless something is known about the light which illuminates the surface. All a surface can be said to possess is a spectral reflection characteristic. If the spectral energy distribution of the incident illumination is known, the product of the two characteristics, wavelength by wavelength, can lead to some knowledge of the colour which the surface will appear to have, although this is also affected by other factors such as the colour of nearby surfaces.

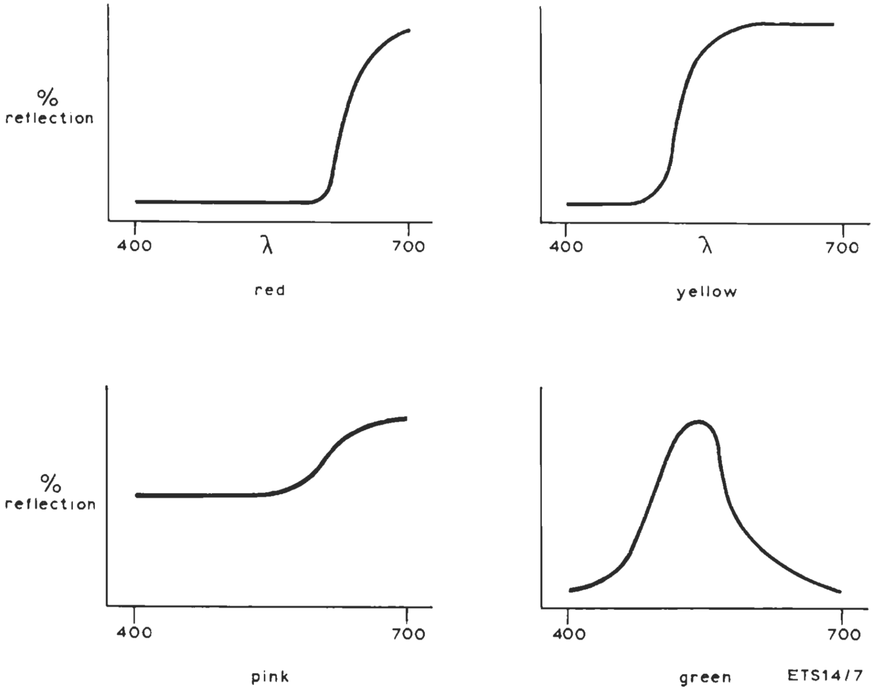


Fig. 2.6 Examples of spectral reflection characteristics of four coloured surfaces

Light sources are of two main types, those emitting a continuous spectrum and those emitting light at one or more discrete wavelengths. Examples of both types of spectra are given in Fig. 2.7.

The first type produces light by heating a filament or a gas to a high temperature, the second by maintaining an electrical discharge through a gas or vapour. An ordinary tungsten filament lamp is an example of the first type whilst the familiar yellow sodium street lamp is an example of the second.

Fluorescent lamps produce a continuous spectrum on which is superimposed a number of strong spectral lines. In colour television only continuous spectrum radiators of the tungsten lamp type are employed. The nature of the light they emit is controlled almost entirely by the temperature of the filament and we shall finish this chapter with an account of the relationship between colour and temperature.

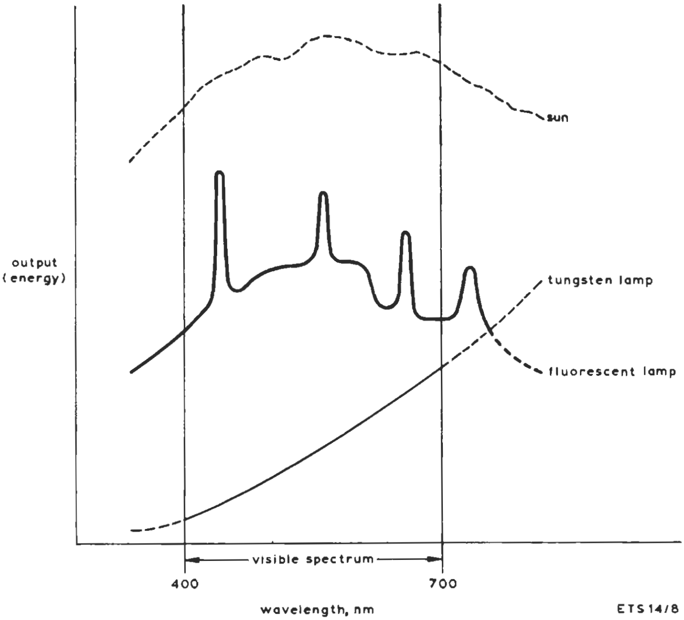


Fig. 2.7 Spectra of three light sources

Colour Temperature

A black bodyis one which absorbs all incident radiation: soot is a good example. When such a body is heated to incandescence (and providing it does not decompose in the process) it gives out light in a continuous spectral band. Such a radiator is described as a full radiator and its temperature entirely specifies the spectral distribution of the light energy radiated from it.

A hole in the side of a spherical electrical furnace is a very good approximation to a full radiator. When the furnace is cold, all the radiation which falls on the hole enters the furnace and is lost by multiple reflections inside. As the furnace temperature rises the radiator (the hole) begins to emit light the character of which is entirely determined by the furnace temperature. At low temperatures, say 1000° C, the energy radiated is small and the light emitted is red. As the temperature rises the peak of this spectral distribution curve moves towards the blue end of the spectrum and the total energy, represented by the area under the curve, increases as shown in Fig. 2.8. The wavelength of peak energy λ_{max} is related to the full-radiator temperature, T, in degrees Absolute*, by the simple expression

$$\lambda_{max}T = \text{constant.}$$

For the sun's radiation the wavelength of peak energy corresponds very closely to the wavelength of maximum eye sensitivity (i.e. a yellow colour).

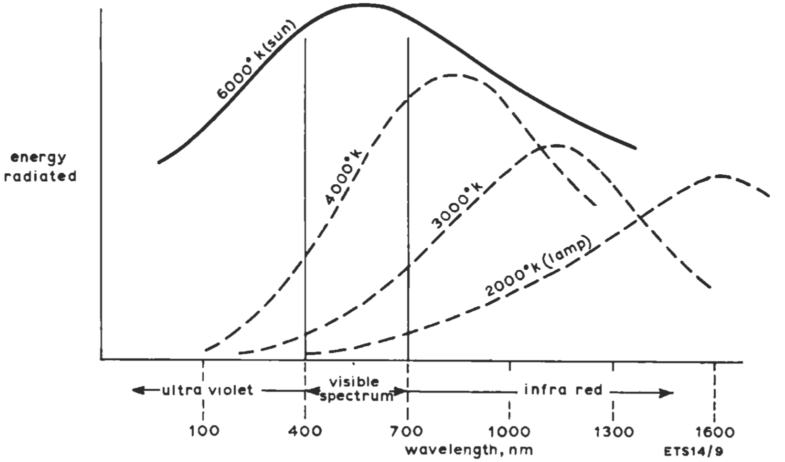


Fig. 2.8 Colour temperature. Typical spectral curves for the radiation from a full radiator

A light source such as a tungsten lamp can be matched in colour by the light from a full radiator raised to a specific temperature. This temperature is the *colour temperature* of the light source. If now a filter is placed before the light source so that the spectral response of the radiation is modified to contain less red and relatively more blue, a full radiator would need to be taken to a higher temperature than before to match the colour of the radiation leaving the filter. Thus by means of a filter the colour temperature of a light

*Degrees K (i.e. degrees Absolute or Kelvin) = Degrees C + 273.

source may be modified; either increased by use of a bluish filter or decreased by use of a reddish one. Of course the response of the filter must be such that the light emerging from it has a spectral response similar to that of the full radiator. No amount of furnace-temperature adjustment would permit the colour temperature of green radiation to be obtained because the colour green is not associated with the broad spectral response of a full radiator at any temperature.

Colour-temperature-correction Filters

It is more convenient to fit colour-temperature-correction (C.T.C.) filters to the camera lens than in front of the luminaire and such filters are usually calibrated in *mired* values. 'Mired' stands for Micro Reciprocal Degrees. When light of a particular colour temperature $T_1{}^0$ K passes through a C.T.C. filter it is modified to $T_2{}^0$ K. Unfortunately the difference $(T_1 - T_2)$ is not independent of T_1, in other words a particular C.T.C. filter does not raise (or lower) a colour temperature by the same amount irrespective of the colour temperature of the light source. A relatively simple relationship does however, exist. For a given filter the difference between the reciprocals of the absolute temperatures, i.e. $(1/T_1 - 1/T_2)$, is constant. To avoid small fractions this difference is multiplied by 10^6 to give the C.T.C. filter its mired value. For example suppose a C.T.C. filter raises the colour temperature of a tungsten lamp radiation from 3000° K to 3500° K. It must be a bluish filter to achieve an increase in colour temperature; it must also have a mired value of $10^6\,(1/3000 - 1/3500)$, i.e. 48 mired approximately. If now this filter were used in conjunction with a source of 4000° K the mired value of which is $10^6/4000$, i.e. 250, the new mired value would become 250 — 48 or 202 mired.

This corresponds to a colour temperature of about 5000° K and shows the importance of calibrating a colour-temperature meter in mired values.

Colour-temperature Meter

Simple colour-temperature meters measure the relative amounts of red and blue radiation in the incident light. The light passes through a red filter and falls upon a photovoltaic cell which causes a current to flow through the associated microammeter. By controlling the total amount of light entering the instrument this current can be adjusted to a definite value and establishes the amount of red in the incident radiation at a definite level. A lever is now moved to replace the red filter by a blue one. The pointer of the micro-ammeter now reads colour temperature or mired value directly. When there is a relatively large amount of blue the deflection is greater and this corresponds to a high colour temperature.

3

PRINCIPLES OF COLORIMETRY

Introduction

Colorimetry is the science of the numerical representation of colour and the first requirement in introducing a system of measurement and number into a new field is the definition of the unit or units to be employed. We have mentioned in chapter 2 that suitable additive mixtures of three primary lights, red, green and blue will match most colours and what is required now is a unit in which to specify the amounts of the three primaries employed in a given match. One unit, the lumen, is already available, and using this we may say that x lumens of colour C is matched by l lumens of red primary together with m lumens of green primary and n lumens of blue primary.

We could express this match in mathematical form thus

$$x(C) \equiv l(R) + m(G) + n(B),$$

where the letters in brackets represent colours and the other letters represent the number of lumens. Such a measurement could readily be made using the eye-response photocell mentioned in chapter 2. It would be found that

$$x = l + m + n.$$

That is, the total number of lumens in the colour to be matched is the sum of the lumens in the red, green and blue primary beams. Independent reference to the eye's response confirms this observation which is known as Grassman's Law. This simple relationship describing the response of the eye is worthy of note: most physiological sensations are non-linear. The linear response of the eye leads to a great simplification in the subject of colorimetry.

White Match

When white is matched by a suitable mixture of the three primaries it is found that the contribution of each of the primaries is very different from that of the other two. For example, if three primaries are chosen with exactly the colours of the phosphors standardised for use in colour television, 1 lumen of a standard white is matched by 0·3 lumen of red, 0·59 lumen of green and 0·11 lumen of blue. More will be said later on the choice of standard white. In colorimetry it is considered unsuitable to use a unit of measurement such as the lumen which requires different amounts of the three primaries to give a white match. It is better to regard white as a colour in which the three primaries make equal contributions. This was assumed when white was shown at the centre of gravity of the equilateral triangle employed in chapter 2 to illustrate additive colour mixing.

Trichromatic Units (T unit)

A new unit, the T unit, is therefore employed in which equal amounts of red, green and blue are required in a white match. Thus we have

$$1 \text{ lumen of standard white} \equiv 1 \text{ T unit of red} + 1 \text{ T unit of green} + 1 \text{ T unit of blue}$$

$$\text{or } 1 \text{ lumen of white} \equiv 1(R) + 1(G) + 1(B)$$

where (R) etc., means T units of Red, etc.

Comparing this expression with that stated earlier for the colour television primaries we have

1 T unit of red = 0·3 lumen
1 T unit of green = 0·59 lumen
1 T unit of blue = 0·11 lumen

Measurement of the primary contributions to a particular colour match in T units can be direct and does not require a conversion from lumens to T units. Suppose three photocells each with a meter and sensitivity control are available and each monitors the light output from a single primary source as shown in Fig. 3.1. The three primary lights are superimposed on a screen and their intensities are adjusted to match 1 lumen of standard white. The photocell sensitivities are now adjusted so that each reads unity (1 T unit). Any colour may now be matched and the contributions of the three primaries to the match are indicated directly by the meters in T units.

Because of the convenience of Grassman's Law it has been applied to measurements employing T units by defining the number of T units of mixture colour as the sum of the number of T units in the primaries employed.

For the white match this leads to the conclusion that 1 lumen of white is equal to 3 T units, i.e.

$$1 \text{ lumen of white} = 3(W) \equiv 1(R) + 1(G) + 1(B)$$

$$\text{or } 1(W) \equiv \tfrac{1}{3}(R) + \tfrac{1}{3}(G) + \tfrac{1}{3}(B).$$

In words this last colour equation reads:—One T unit of white is matched by one third of a T unit of primary red plus one third of a T unit of primary green plus one third of a T unit of primary blue. Knowing the luminance of 1 T unit of each of the primaries we can determine the luminance of 1 T unit of white and this must, of course, be ⅓ lumen.

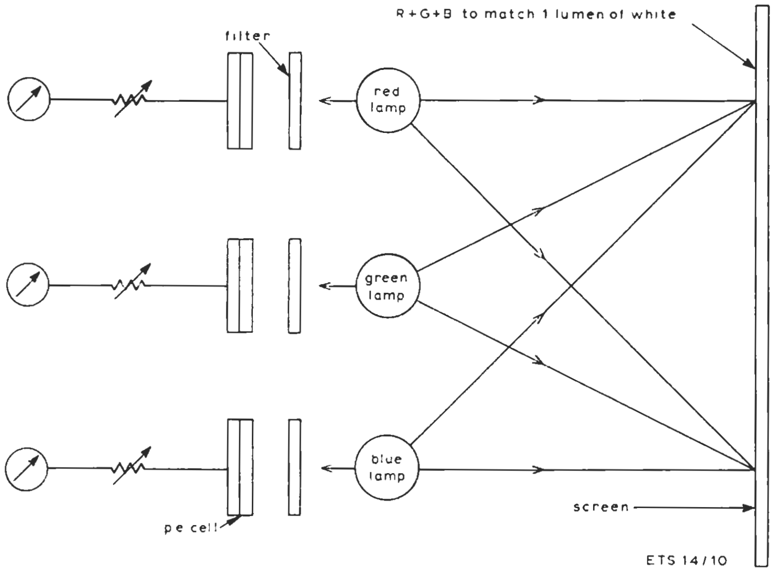


Fig. 3.1 Colour matching. Experiment to illustrate use of T units

Colour and Luminance

At this point the difference between colour and luminance or brightness can be distinguished. Doubling or trebling the amounts of each primary in the colour match doubles or trebles the luminance of the resultant whilst maintaining its colour. It follows then that the total number of T units in the match determines the luminance whilst the ratio of the three primary contributions determines the colour.

Luminance or Brightness of a Match

Suppose a certain colour patch on a screen is matched by the three primaries previously employed and that measurements give the following colour equation

$$\textit{Colour } C \equiv 18(R) + 20(G) + 12(B)$$

Because

$$1{\cdot}0(R) = 0{\cdot}3 \text{ lumen,}$$
$$1{\cdot}0(G) = 0{\cdot}59 \text{ lumen,}$$
$$\text{and } 1{\cdot}0(B) = 0{\cdot}11 \text{ lumen,}$$

the luminance of the colour C is given by

$$18 \times 0{\cdot}3 + 20 \times 0{\cdot}59 + 12 \times 0{\cdot}11 = 18{\cdot}5 \text{ lumens.}$$

The number of T units of colour is

$$18 + 20 + 12 = 50.$$

Colour

The statement immediately above may be written

$$50(C) \equiv 18(R) + 20(G) + 12(B)$$
$$\text{or } 1{\cdot}0(C) \equiv 0{\cdot}36(R) + 0{\cdot}4(G) + 0{\cdot}24(B).$$

This last equation expresses the colour match for 1 T unit of the colour C but the information concerning the luminance of C is lost. The ratios 0·36, 0·4 and 0·24 however, precisely determine the colour C and furthermore because $0{\cdot}36 + 0{\cdot}4 + 0{\cdot}24 = 1$, only two of these ratios need be employed to specify colour C. These numbers are referred to as the *trichromatic coefficients* of the colour and are usually represented by r, g, b, where

$$r + g + b = 1.$$

Colour Triangle

Once a colour has been specified by the use of only two numbers, say r and g, it may be plotted on a graph the axes of which are r and g as shown in Fig. 3.2. The primary colours of the measurement system are at the corners of the colour triangle. When $r = 1$, $g = b = 0$ and this point represents primary red. Similarly $g = 1$, $r = 0$ corresponds to primary green and $r = 0$, $g = 0$ (i.e. $b = 1$) corresponds to primary blue. The point representing white necessarily has $r = g = 0{\cdot}33$: it is the centre of gravity of the triangle.

Further, as any mixture of two colours must lie on the line joining the two colour points, it follows that all colours which can be matched by the three primary colours must lie within the area of the triangle.

Points on the line RG represent colours containing red and green only. No blue is present in such colours and we can thus define the line RG as one for which $B = 0$. Similarly $R = 0$ for line BG and $G = 0$ for line BR.

Spectrum Locus

Once it becomes possible to plot a colour as a point it is natural to attempt to plot the colour of each wavelength or at least each just noticeably different spectral colour on this diagram. Here a difficulty is encountered for with most if not all spectral colours it is impossible to make an accurate match with any combination of the three chosen primaries. Spectral or sodium yellow for example cannot be matched by any combination of the red and green primaries. If, however, the colorimeter in which the colour matching and measurement is made allows any one of the primaries to be mixed with the colour to be matched then a colour equation can be reached. For example, if the primary blue of the instrument is added to the sodium yellow, the diluted or desaturated yellow so obtained can be matched by a suitable mixture of red and green. The colour equation can then be written. In arbitrary figures it might be found that

$$\textit{sodium yellow} + 5(B) \equiv 20(R) + 25(G).$$

In words this means that if 5 T units of blue are added to the sodium yellow, the resultant colour can be matched by a mixture of 20 T units of red and 25 T units of green. The equation can be re-written

$$\textit{sodium yellow} \equiv 20(R) + 25(G) - 5(B).$$

As before the number of T units of the colour to be matched is obtained by adding the contributions of the primaries, (here $20 + 25 - 5 = 40$). Thus

$$40(S.Y.) \equiv 20(R) + 25(G) - 5(B)$$
$$\text{or } 1{\cdot}0(S.Y.) = 0{\cdot}5(R) + 0{\cdot}625(G) - 0{\cdot}125(B)$$

The required trichromatic coefficients are therefore

$$r = 0{\cdot}5,\ g = 0{\cdot}625,$$

which total more than unity because blue must be added to the yellow (not to the red and green) to obtain a match.

As shown in Fig. 3.2 this point lies outside the triangle of the primary colours, which implies that it cannot be matched by any mixture of the three. In this way colour points for all the spectral colours can be obtained and the line joining them is the spectrum locus, Fig. 3.2. Points lying on the line joining the ends of the spectrum locus represent colours which are mixtures of spectral red and blue, i.e. the purples. These are non-spectral colours; i.e. they are not found in the spectrum.

Because all colours are combinations of spectral colours it follows that the points representing all real colours lie within the boundary of the spectrum locus and the non-spectral purples. No real colour can be represented by a point outside this area.

Colours of Negative and Zero Brightness

1 T unit of colour is associated with a definite lumen value. The luminance

Y of 1 T unit of colour is given by

$$Y = 0{\cdot}3r + 0{\cdot}59g + 0{\cdot}11b$$

where r is the amount of red primary in T units and each T unit of red is equal to 0·3 lumen. Similarly g represents the amount of green primary in T units, each T unit being equal to 0·59 lumen. Finally b is the amount of blue primary in T units, each T unit equalling 0·11 lumen.

As negative trichromatic coefficients have now arisen it becomes possible to imagine colour points representing colours having zero brightness. Putting

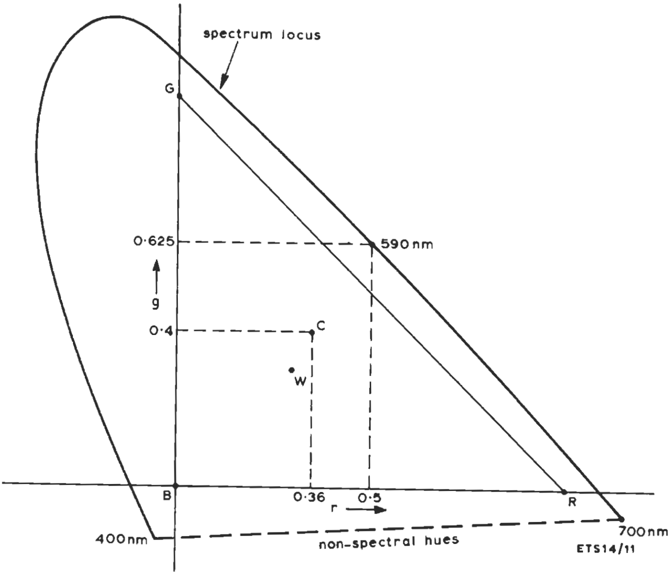


Fig. 3.2 Colour triangle and spectrum locus

$Y = 0$ and substituting for b from the equation $r + g + b = 1$ we have

$$0 = 0{\cdot}3r + 0{\cdot}59g + 0{\cdot}11(1 - r - g)$$
$$\text{i.e. } 0 = 0{\cdot}19r + 0{\cdot}48g + 0{\cdot}11$$

which is the equation of a straight line. Its position on the colour diagram can be plotted by first putting $r = 0$ (which gives $g = -0{\cdot}11/0{\cdot}48 = -0{\cdot}23$) and then putting $g = 0$ (which gives $r = -0{\cdot}11/0{\cdot}19 = -0{\cdot}58$). The required line is that joining $(0, -0{\cdot}23)$ to $(-0{\cdot}58, 0)$ as shown in Fig. 3.3. It is called the *alychne* (without light) and is the locus of points representing colours of zero brightness. Not surprisingly it does not pass through the spectrum locus, confirming that no real colours exist which have zero brightness! The alychne has great significance both in colour television and in the international system of colour specification dealt with in chapter 5. Points below the alychne represent non-real colours of negative brightness!

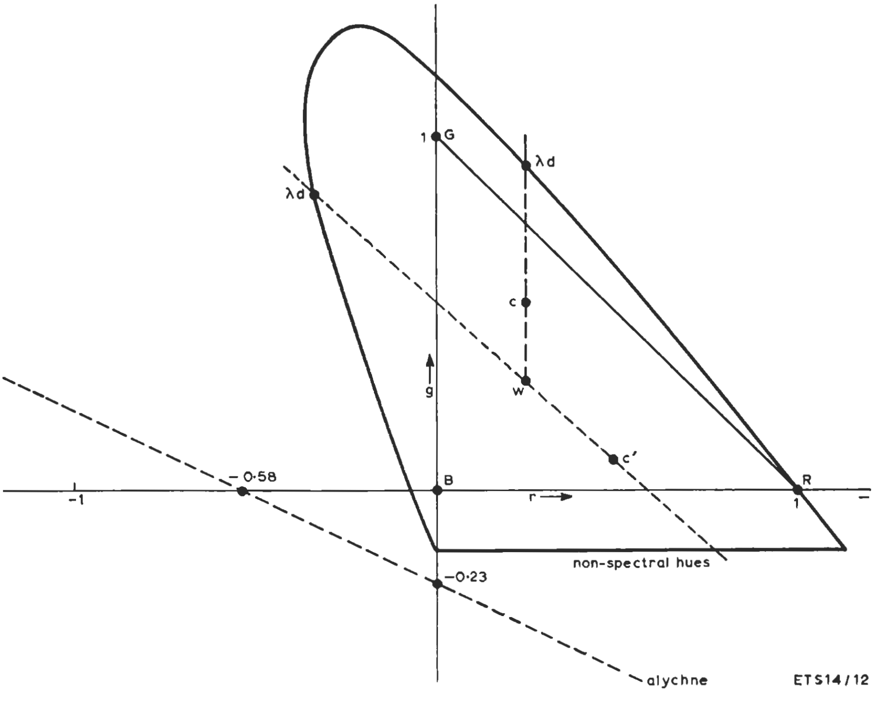


Fig. 3.3 Colour triangle and alychne

Colour Specification

Enough has been said in this chapter to permit two methods of colour specification to be formulated.

The first system employs the trichromatic coefficients, say *r* and *g*. These two coefficients do not completely specify the colour however, without knowledge of the measurement primaries employed and the nature of the standard white.

The second system is more satisfactory. Suppose colour *C*, Fig. 3.3, is to be specified. A line is drawn through *C* and the white point to cut the spectrum locus at some point corresponding to a colour of known wavelength. It follows that the colour could be matched by a suitable mixture of this wavelength (the dominant wavelength) and the standard white. The distance of the colour point *C* from the white point expressed as a fraction of its distance from the spectrum colour is called the *purity* or *saturation*. Thus saturation and dominant wavelength specify the colour and only a knowledge of the standard white is necessary. If the line through the colour point *C* cuts the non-spectral colour boundary, it must be produced in the opposite direction to cut the spectrum locus. The complementary dominant wavelength is then used in the specification.

Meaning of White

White has been referred to a number of times and is a most important colour used in the initial calibration of the measurement primaries. Unfortunately several whites are used as standards depending on the circumstances. The following are four whites commonly employed.

Illuminant A

This is the white of artificial lighting using tungsten filament lamps and corresponds to a colour temperature of 2850° K.

Illuminant B

This white corresponds to standard daylight and has a colour temperature of 4800° K.

Illuminant C

This is a white of colour temperature 6600° K and is used in colour television.

Equal-energy White

This white is slightly bluer than illuminant C and corresponds to a spectrum in which all wavelengths carry the same energy. It is accepted as a standard white by the international body concerned with colour specification (C.I.E.).

4

FUNDAMENTALS OF COLOUR TELEVISION

Introduction

In this chapter the colour theory developed in chapter 3 is applied to the basic problems of colour television. Some of the optical arrangements peculiar to the colour camera are discussed together with the structure of the shadow-mask picture tube.

The chapter concludes with an examination of the problems raised by the need for compatibility and the bandwidth saving which a knowledge of colour vision allows.

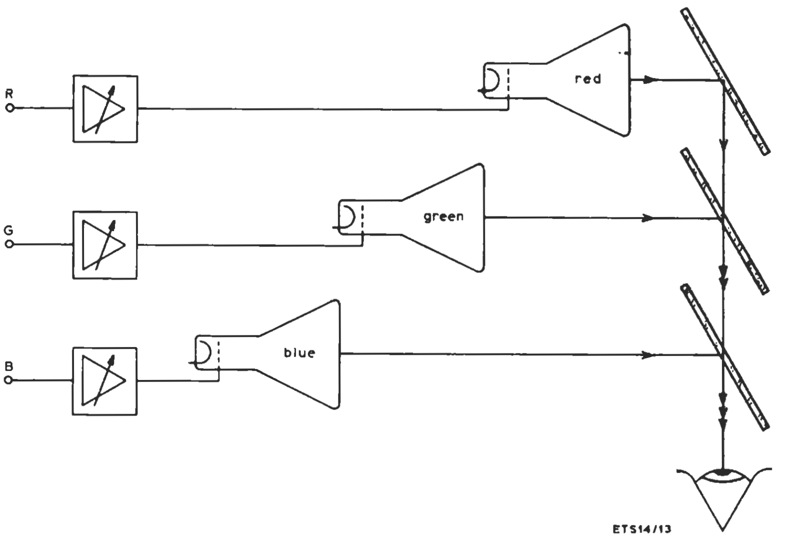


Fig. 4.1 Production of a colour picture by use of three cathode ray tubes

Colour Analysis and Synthesis

The synthesis of a colour picture is achieved by the registration of three pictures in red, green and blue. A simple arrangement of three cathode ray tubes, Fig. 4.1, can be used together with semi-transparent mirrors for the purpose of registering the three pictures. Picture information can be supplied to the inputs of the three tubes via amplifiers and it is possible so to adjust the gains of the amplifiers that steady voltages applied to the inputs of the amplifiers (assumed direct-coupled) give a black and white raster. This arrangement has the advantage that with normal R, G, B input signals, by simply paralleling the three inputs a black and white picture is obtained irrespective of the coloration of the original scene.

The voltages R, G and B are obtained from a colour camera and in this three camera tubes are required, one producing an output corresponding to the red picture brightness, a second corresponding to the green picture brightness and a third corresponding to the blue picture brightness. It follows that the light which is collected from the studio set by the single turret lens of the camera must be split in such a way that each camera tube receives a sharply-focused image from which it can develop the required colour signals. Such a system is shown in Fig. 4.2. Dichroic mirrors are used to split the light into its red, green and blue components. The properties of dichroic mirrors are described later.

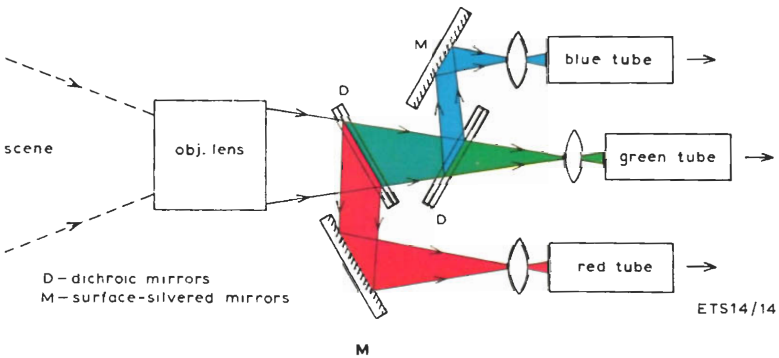


Fig. 4.2 Arrangement of dichroic mirrors in a colour television camera

Thus the analysing system consists of a camera with a single lens from which are derived three pictures, each formed on the photocathode of a separate camera tube, whilst the synthesising system is the three-colour-tube receiver.

There is a definite relationship between the phosphor colours chosen for the receiver and the colour responses of the camera. To determine the required camera colour responses let us suppose an experiment were to be carried out using the arrangement of Fig. 4.1. Further let us assume that the light output from the tubes is linearly related to the input voltages R, G and B; this is not likely in practice but one could arrange for the three amplifiers to have the required non-linear response which would make the assumption true. Let us first assume equal inputs of 1 volt to each channel and adjust the amplifier gains to achieve a white raster, which matches in colour and luminance a comparison full-spectrum white raster. Now replace the comparison white raster by a raster having a narrow-band blue colour, having exactly the energy of the same band in the original white. The *R*, *G* and *B* inputs are adjusted to match this blue as closely as possible in colour and luminance and the three readings are noted. The next band of colour from the spectrum of the original white is now taken and new values of *R*, *G* and *B* obtained and noted. This procedure is repeated for all the colours in the spectrum of the original white and finally curves are plotted showing how *R*, *G* and *B* requirements vary throughout the spectrum; the resulting diagram has the form of the solid lines shown in Fig. 4.3.

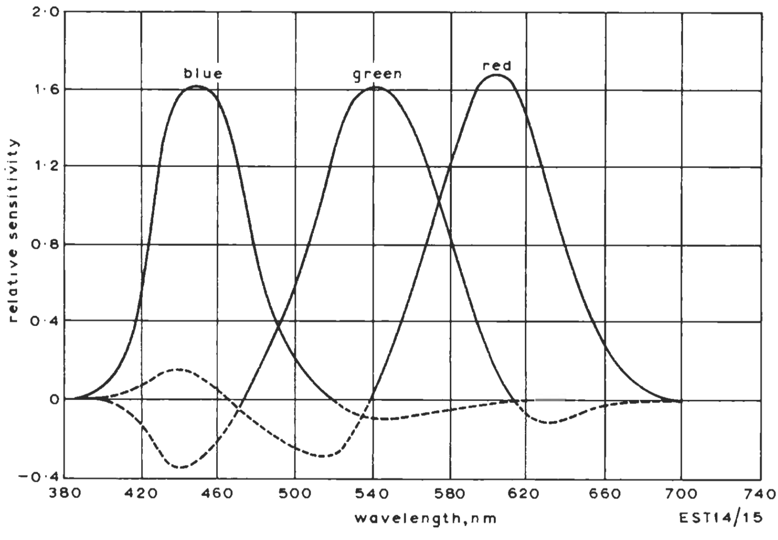


Fig. 4.3 Distribution coefficients for the NTSC phosphor primaries

If it were possible in this experiment to make use of the concept of negative primaries in matching the colours, then the curves finally obtained would contain the negative lobes shown dotted in Fig. 4.3. These are the curves of the distribution coefficients of the NTSC phosphor primaries. If the values of *R* for each colour band are added together, the result is 1 volt and the same is true for the values of *G* and *B*, for if all the colour bands are displayed together the original white raster is produced. Another way of expressing this is to say that the areas under the three curves are equal.

If now the colour camera is presented with narrow bands of colour one at a time from the blue to the red end of the spectrum the outputs *R*, *G* and *B* obtained from the three channels must have exactly the values indicated in

Fig. 4.3. This means that the colour responses of the camera must be the distribution coefficients of the three receiver phosphor colours.

The study of colorimetry in chapter 3 showed however, that it is not possible to find three primary colours which can match all the spectral colours and thus there are certain colours which the three receiver phosphor colours cannot match. This is borne out by the negative values of R, G and B in the curves of Fig. 4.3. It is not possible to obtain a camera with colour responses having negative excursions.

These colour responses depend on the spectral characteristics of the dichroic mirrors and of the photo-cathodes. Final adjustment towards the desired responses is made by use of shaping filters and the relative magnitudes of the responses is adjusted by the use of neutral density filters.

Colour Camera Optical Systems

The physical introduction of dichroic mirrors, shaping filters and neutral density filters between the turret lens of the camera and the three receiving tubes clearly presents an optical problem. This has been solved in a number of ways three of which are described below. Before dealing with these methods a simple description of dichroic mirrors will be given.

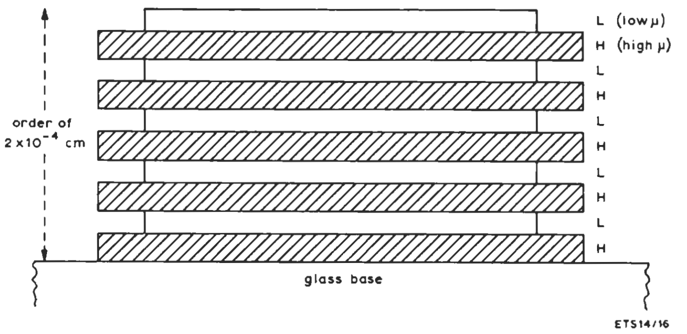


Fig. 4.4 Construction of a dichroic mirror

Dichroic Mirrors

A dichroic mirror has the property of reflecting a spectral band of light whilst transmitting the rest. There is little loss of light by absorption. If the reflected light lies within a band at the red end of the spectrum, the dichroic mirror is described as a *red reflect* type and if the band is at the opposite end of the spectrum the dichroic mirror is a *blue reflect* type.

These effects are achieved by interference occurring in multilayer films which are coated by vacuum evaporation onto a glass base (Fig. 4.4). The layers are of alternatively high and low refractive index material, the high-μ material being zinc sulphide ($\mu = 2{\cdot}3$) whilst the low-μ material is magnesium fluoride ($\mu = 1{\cdot}38$). The latter material is also used in the blooming of lenses. Thicknesses of the individual layers vary from $\frac{1}{8}$ to 1 wavelength and from 5 to 35 layers may be employed. Typical dichroic mirror responses are given in Fig. 4.5.

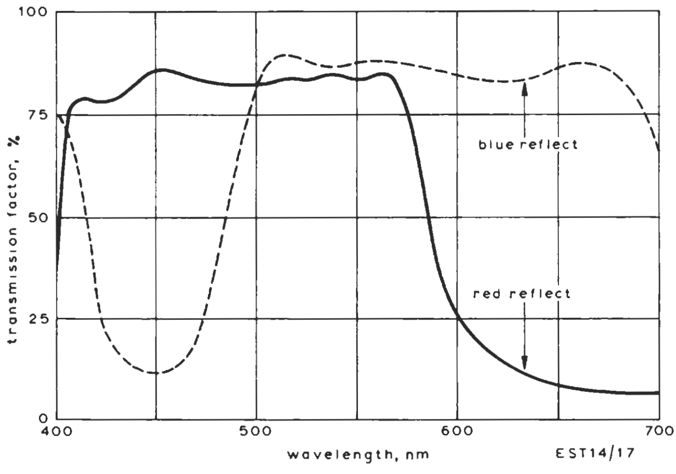


Fig. 4.5 Transmission characteristics of dichroic mirrors

R.C.A. Colour Camera

The optical system for this camera is illustrated in Fig. 4.6. By means of two relay lenses L_3 and L_4, the first image I_1 produced by the turret lens L_1 is reproduced at I_2. The light between L_3 and L_4 is parallel and this is a convenient place for the iris which forms the overall gain control of the system. The space between L_4 and I_2 accommodates the dichroic mirrors, D, whilst the space between L_1 and L_3 contains two optical flats, C, which have the same thickness as the slabs of the dichroic mirrors but are mounted in planes perpendicular to the mirrors to correct the astigmatism which is introduced by the mirrors. They function here by predistorting the optical system, cancelling the distortion introduced later by the dichroic mirrors. Unfortunately the predistortion is too great for the blue component of the beam because this is reflected at the first dichroic mirror and thus passes through glass equivalent to the thickness of a single slab. (The multilayer film is sandwiched between two glass slabs of equal thickness and reflection at the film means a double passage through half the total mirror thickness.) A further slab of optically flat glass, H, is therefore introduced in the blue beam to give full cancellation of the predistortion. The red and blue components both travel through glass which is equal in thickness to twice the thickness of a single mirror, and no further compensation is necessary. The field lens, L_2, refracts the light forming the edges of the image at I_1 through the first relay lens: it forms an image of L_1 on L_3 so that all the light passing through L_1 must also pass through L_3. The field lens has no effect on the final image size.

The spectral characteristics of the available dichroic mirrors are not precisely those demanded for accurate colour analysis. The overall colour responses can be calculated when the colours of the primary phosphors in the colour receiver are known. Ordinary colour glasses are used as shaping filters, S, to adjust the responses of the dichroic mirrors to achieve the overall colour

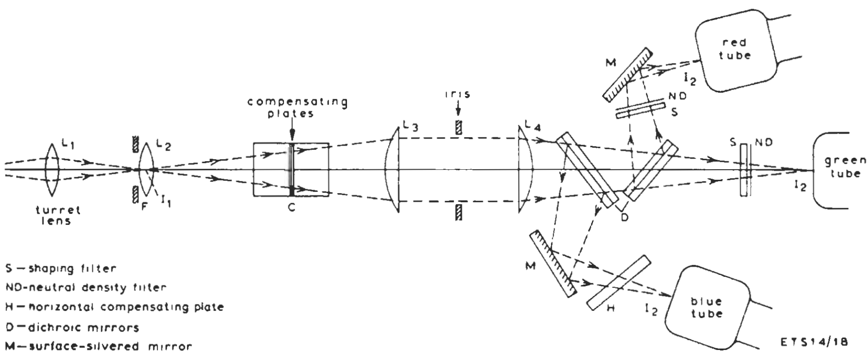


Fig. 4.6 Optical system of R.C.A. colour television camera

responses required. Finally to balance the relative amplitudes of these responses, neutral density filters, ND, are used in two of the beams. These are adjusted in conjunction with the television camera tubes so that the overall sensitivities of the three channels are properly balanced. The turret lens L_1 is moved for focusing in just the same way as an ordinary camera lens. Dichroic mirrors in which the multilayer films are deposited on very thin glass sheets are now being produced; their astigmatism is negligible.

Prism-block Mirror System

A more satisfactory arrangement of the dichroic mirrors is the 'ice-cube' optical system now used in R.C.A. colour schemes and illustrated in Fig. 4.7. The two dichroic layers are in contact with the adjacent faces of a prism and these faces are optically in contact with other glass prisms which present normal surfaces to entrant and emergent beams. This eliminates the astigmatism of the system described above and the consequent need for correcting plates; it also reduces the number of air/glass interfaces and the possibility of unwanted reflections. A plano-concave lens is mounted in front of each camera tube to reduce curvature of the image plane.

Other methods of beam splitting are being investigated and no final solution is yet available.

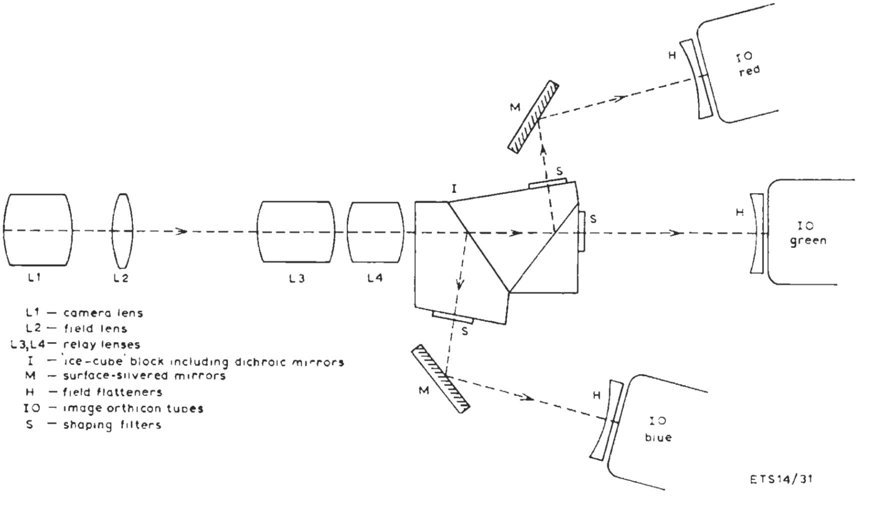


Fig. 4.7 Prism-block optical system for colour television camera

E.M.I. Colour Camera

In this system shown in Fig. 4.8 each camera tube is supplied with its own lens. The dichroic plates, each about four inches square and a quarter of an inch thick, are mounted in front of the lenses, so avoiding the introduction of astigmatism. Trimming or shaping filters are used as before. Variation in focal length is achieved by the use of a 4-position turret in front of the dichroic mirrors. In one position there is merely a hole; in a second, a large convex lens effectively reduces the angle of view of the camera tubes (telephoto lens system) whilst in positions three and four large concave lenses increase the angle of view (reverse telephoto lens system).

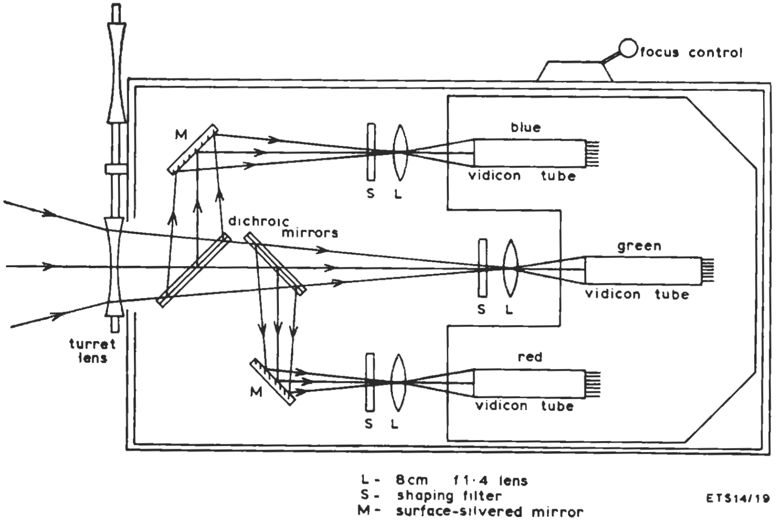
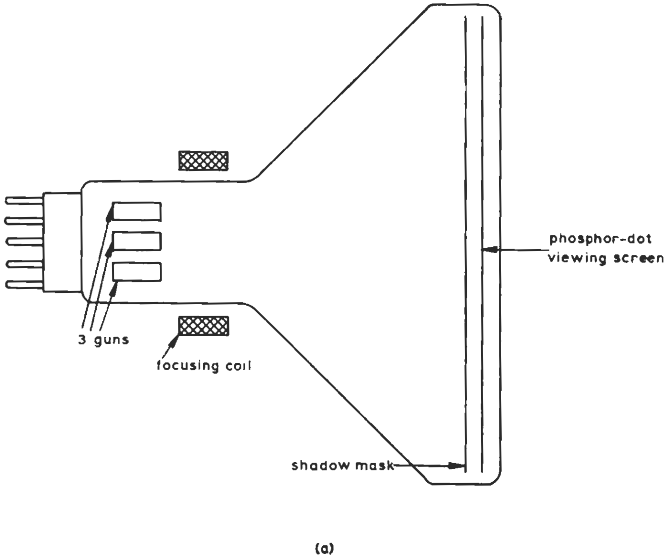


Fig. 4.8 Optical system of E.M.I. colour television camera

Shadow-mask Tube

Various methods have been employed for the display of the colour picture; all require the accurate registration of pictures in red, green and blue. The most successful method to date uses the R.C.A. shadow mask tube (Fig. 4.9). In spite of complex production problems these tubes are now made in increasing numbers and are the accepted type in colour receivers.

The tube consists of three electron guns firing three beams towards the screen, the beams being controlled in intensity by the red, green and blue colour signals applied between grid and cathode of each gun. The beams are focused and converge so that they pass through one of a very large number of tiny holes in a thin metal plate placed a short distance from the screen. This plate is the *shadow mask* which gives the tube its name. On the far side of the shadow mask the three beams diverge and strike the screen at three different spots. It is arranged that where the red controlled beam strikes the screen there is a red phosphor dot and where the other beams strike there are similarly green and blue phosphor dots. The shadow effect of the mask is such that only the red dots can be illuminated by the electron beam from the red gun, the green dots by the beam from the green gun and the blue dots by the beam from the blue gun. The screen is covered with almost a million



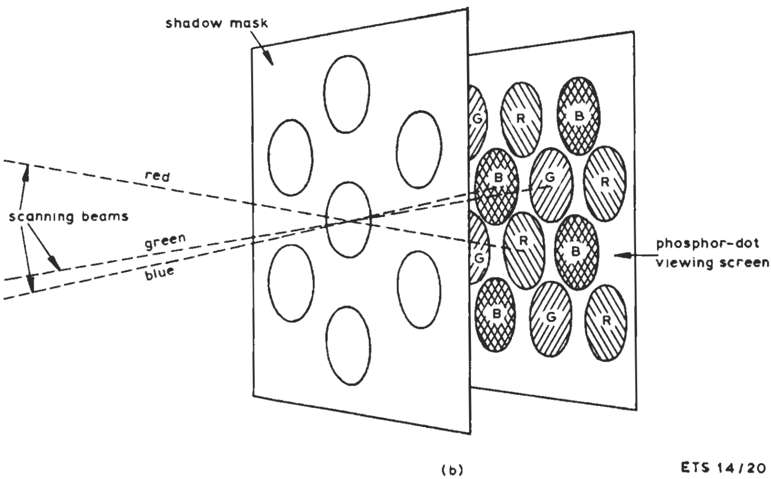


Fig. 4.9 R.C.A. shadow-mask picture tube (a) with details of the mask and phosphor dot screen (b)

phosphor dots, one third of each colour so that at a short distance from the screen the dots cannot be resolved by the eye and the resultant colour is determined by the relative excitation of the three types of dots. A single set of scanning coils deflects the three beams together to produce a raster.

Compatibility

The simplest colour television system involves the transmission of a full picture signal from the red camera tube to the red gun in the display tube and full picture signals also for the green and blue guns. The total transmission bandwidth for such a system is at least three times that of a monochrome television system. Moreover none of these three transmissions on its own corresponds to the black and white, i.e. luminance signal of the monochrome system. Thus a monochrome receiver would be unable to receive a high-quality picture from a colour transmission of this type. The ability of the colour signal to produce a satisfactory picture in black and white on a monochrome receiver is known as *compatibility* and is regarded as essential in any public colour television system.

Reverse Compatibility

It is also considered desirable that the system of transmission for the colour programme should be such that a colour receiver can reproduce a normal black and white transmission as a black and white picture of high quality. This is the criterion of *reverse compatibility.*

Requirements for Compatibility and Reverse Compatibility

Three signals are necessary to transmit colour and luminance information, and in the simplest transmission system these are the R, G and B signals. However, for compatibility one signal must be the luminance signal Y and this can be obtained from the R, G and B signals. Suppose the colour camera is aimed at a white surface of luminance 1 ft-lambert and that under these circumstances the three colour signals R, G and B are each adjusted to 1 volt. At the receiver the white surface is reproduced, again we will assume with a 1 ft-lambert brightness. The luminance of the red contribution is 0·3 ft-lambert, that of the green 0·59 and of the blue 0·11. Thus to produce a luminance signal, that is a voltage proportional to luminance Y of the normal monochrome television type, we need to add 0·3 of the red channel voltage, 0·59 of the green channel voltage and 0·11 of the blue. Thus we have

$$Y = 0{\cdot}3R + 0{\cdot}59G + 0{\cdot}11B.$$

This can be done using potentiometers to select the appropriate fraction of each channel voltage, each followed by a valve or transistor the three of which have a common output load. The current in the load contains contributions corresponding to all three inputs and is thus proportional to the sum of the inputs.

We still need to transmit three signals in a colour transmission however, and if one is Y we need two other signals. A normal monochrome receiver can then respond to Y only and reproduce a high-quality black and white picture. The two other signals, the chrominance signals, could be R and B because given Y, R and B the voltage G can be obtained as indicated below.

$$0{\cdot}59G = Y - 0{\cdot}3R - 0{\cdot}11B$$

$$\therefore G = \frac{Y - 0{\cdot}3R - 0{\cdot}11B}{0{\cdot}59}$$

This expression shows that two subtraction processes are required to obtain the G signal. A signal can be subtracted from another by reversing its phase and then adding it to the other by the method described above.

In a system based on these assumptions a colour receiver tuned to a black and white transmission would reproduce a picture in green for there are no R or B signals. Reverse compatibility requires that the chrominance signals are zero for black and white pictures. Thus a colour transmission of a black and white picture should contain only the Y signal and is then identical with a monochrome transmission. Such a system is obtained by transmitting the three signals Y, $(R - Y)$ and $(B - Y)$. $(G - Y)$ is not chosen because Y is often nearly equal to G, making $(G - Y)$ a very small and therefore noisy signal. For any shade of grey $R = G = B = x$ volts. Thus

$$\begin{aligned} Y &= 0{\cdot}3x + 0{\cdot}59x + 0{\cdot}11x \\ &= x \end{aligned}$$

Hence for the grey scale $R - Y = 0$
$B - Y = 0$

At the receiver the voltages R, G and B can be derived from Y, $(R - Y)$ and $(B - Y)$. The Y signal carries the full luminance information and the chrominance signals carry none. If Y, $(R - Y)$ and $(B - Y)$ are regarded as transmission primaries then $(R - Y)$ and $(B - Y)$ lie on the alychne and Y lies at the white point.

Bandwidth

So far the luminance and chrominance signals have each been assumed to have the full bandwidth of the system. Thus a colour transmission requires three times the bandwidth of a monochrome system. The Y signal must certainly have this full bandwidth (3 Mc/s for 405 lines and 5·5 Mc/s for 625 lines) but a knowledge of colour vision allows a better choice of chrominance signals and a reduction in bandwidth. As coloured objects are reduced in size blues become indistinguishable from dark shades of grey and yellows appear as whites (light shades of grey). Reds remain clearly distinct from blue-greens. With further decrease in size, reds and blue-greens themselves become indistinguishable from greys and for very small objects or fine picture detail only brightness contrast is perceivable. In the region of medium-fine colour detail where a blue-to-yellow colour excursion is seen as a grey scale, colours can be matched with considerable accuracy by a two-colour system employing orange and cyan as primaries. In other words the points representing all colours in small patches lie on a line from orange to cyan. The electrical signal which controls this orange-to-cyan transition is known as the I signal. Colours between green and magenta are controlled by the Q signal. Taking full advantage of the eye's colour response, the required colour television signals are formulated as follows:—

1. Full bandwidth is employed for the luminance signal Y.
2. For large-area colour corresponding to a band up to 0·8 Mc/s, two chrominance signals are available resulting in full three-colour reproduction. These are the I and Q signals and their derivation from the $(B - Y)$ and $(R - Y)$ signals is dealt with later in this chapter.
3. For medium-fine detail lying in the band 0·8 to 1·6 Mc/s, only one chrominance signal is available resulting in colour reproduction along an orange-cyan axis; this is the I signal.
4. For fine picture detail no chrominance signals are transmitted and fine detail is reproduced only by the luminance signal.

Thus for the 625-line system we have:

Signal	*Bandwidth (Mc/s)*
Y	5·5
I	1·6
Q	0·8

Colour Television Systems

These signals are employed in the NTSC* and PAL* colour television systems to enable full advantage to be taken of the eye's colour characteristics. SECAM*, the French transmission system employs chrominance

*NTSC	National Television Systems Committee	(U.S.A.)
PAL	Phase Alternating Line	(Germany)
SECAM	Sequential Colour with Memory	(France)

signals of equal bandwidth, lying partway between the *I* and *Q* bands given above.

Although this supplement is not principally concerned with transmission systems, the following brief considerations of NTSC, SECAM and PAL will assist the understanding of the significance of the chrominance signals referred to above.

In all these systems the overall bandwidth requirement for colour transmission is the same as for the monochrome system. This is achieved by modulating a sub-carrier, having a frequency within the luminance band, with the chrominance signals. The frequency of the sub-carrier is such that the dot pattern it produces is hardly visible.

If an oscillator output is connected to the input of a television picture tube, severe patterning takes place and the patterns become stationary when the oscillator frequency is a multiple of the line frequency. As the oscillator frequency rises through the luminance band the pattern becomes finer, eventually becoming a series of dots as the beam intensity fluctuates rapidly up and down. If now the oscillator frequency is so locked to line frequency that the dot pattern of one field lies exactly between the dots produced two fields later then persistence of vision will cause the dot pattern to go to a minimum. This is the frequency chosen for the colour sub-carrier.

NTSC

In this system the *I* and *Q* signals are used to modulate the sub-carrier. To do this, quadrature modulation is employed. This is achieved by generating from the sub-carrier a signal in quadrature (i.e. at 90° phase difference)

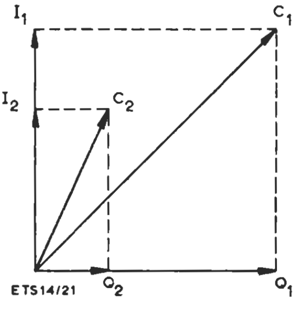


Fig. 4.10 Vector addition of I and Q signals

with it but of course at sub-carrier frequency. These two signals are separately amplitude-modulated with the *I* and *Q* signals in such a way that the carrier is suppressed in each case. They are then added together. Fig. 4.10 shows that the addition of two vectors of varying length result in a vector of varying length and phase. The composite sub-carrier signal which is said to be quadrature-modulated is, in fact, both phase- and amplitude-modulated. The amplitude of the resultant vector represents saturation; the phase represents hue.

This modulated sub-carrier is now added to the luminance signal and bandwidth restriction removes part of the upper sideband of the I signal. Where however, the I and Q signals overlap both are double sideband as shown in Fig. 4.11. This is important if cross-talk is to be avoided in the process of detection.

Use of a suppressed-carrier system means that when the chrominance signals are zero, as they are for all greys in the picture, there is no unmodulated sub-carrier present in the transmission and interference is zero. At the receiver synchronous detection is employed to extract the two chrominance signals from the transmission and this process requires a re-introduction of

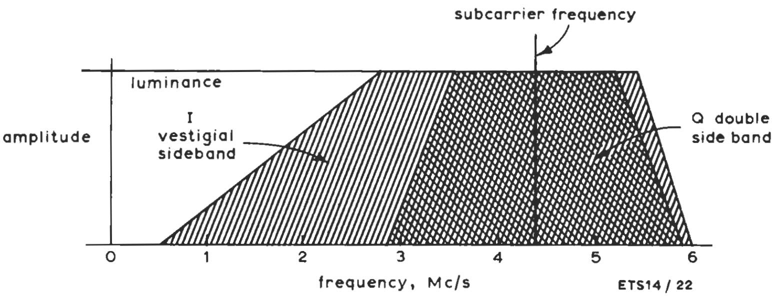


Fig. 4.11 Spectrum of 625-line NTSC colour signal

the sub-carrier at exactly the correct frequency and phase. For this purpose a burst of a few cycles of sub-carrier (known as the *colour burst*) is transmitted during the back porch and is used to synchronise the sub-carrier oscillator in the receiver.

Sub-carrier Vector Diagram

Consider the modulation of the sub-carrier quadrature components by the chrominance signals $(R - Y)$ and $(B - Y)$. The following table gives the values of $(R - Y)$ and $(B - Y)$ when the primary colours, R, G and B have values of 1 volt or 0.

$$Y = 0{\cdot}3R + 0{\cdot}59G + 0{\cdot}11B.$$

Colour	*Channel Voltages*	*Y*	*R* − *Y*	*B* − *Y*
Red	B = 0 G = 0 R = 1	0·3	+0·7	−0·3
Green	B = 0 G = 1 R = 0	0·59	−0·59	−0·59
Blue	B = 1 G = 0 R = 0	0·11	−0·11	+0·89
Magenta	R = 1 B = 1 G = 0	0·41	+0·59	+0·59
Cyan	R = 0 B = 1 G = 1	0·7	−0·7	+0·3
Yellow	R = 1 G = 1 B = 0	0·89	+0·11	−0·89
White	R = 1 G = 1 B = 1	1	0	0

The vector diagram of Fig. 4.12 represents $(R - Y)$ and $(B - Y)$ in addition to the colour burst vector in antiphase to $(B - Y)$ which is used in the receiver for detection.

Any pair of quadrature axes can be employed to specify the position of the resultant vector and if one of such a pair lies along the orange-cyan direction the other will lie along the green-magenta line. These are the I and Q axes and lie as shown in the diagram. They may be derived from the $(R - Y)$ and $(B - Y)$ signals or directly from the R, G and B signals by suitable matrices. If then medium fine-detail is being transmitted there is no Q signal and colours are reproduced lying between orange and cyan.

In practice fractional values of $(R - Y)$ and $(B - Y)$ are used for modulation of the sub-carrier to avoid difficulties caused by overmodulation of the transmitter and interference with sync pulses. For example a low luminance voltage of 0·11 obtained when blue is being transmitted can hardly have a sub-carrier of amplitude 0·89 volts superimposed without the chrominance signal extending well below black level and interfering with the synchronising

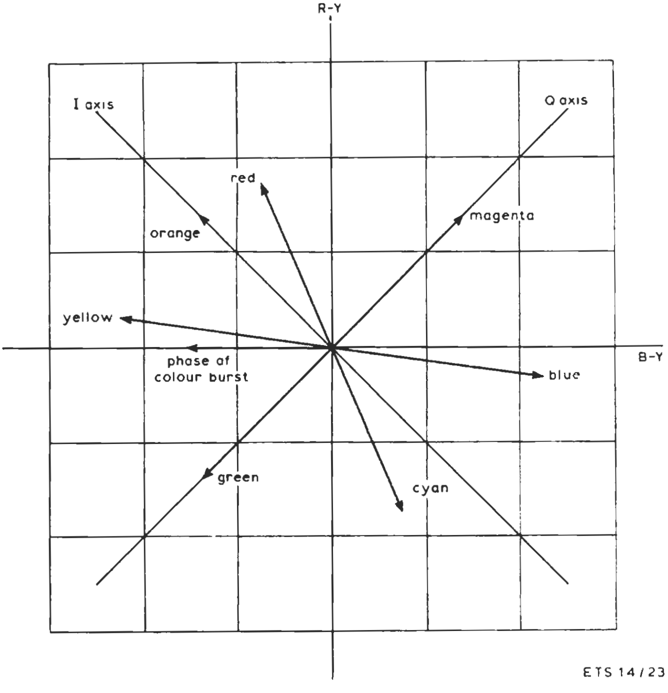


Fig. 4.12 Sub-carrier vector diagram

pulses. Similarly when yellow is being transmitted the luminance signal has an amplitude of 0·89 volts and a $(B - Y)$ chrominance signal of 0·89 volts peak is superimposed. This would take the composite signal to 1·78 volts and cause overmodulation of the transmitter. To avoid these effects the signals used to modulate the sub-carrier are smaller than $(R - Y)$ and $(B - Y)$, being given by $(R - Y)/1{\cdot}14$ and $(B - Y)/2{\cdot}03$. The consequent effects on the I and Q axes are not dealt with here: it is hoped to give further more detailed consideration in a supplement on colour systems.

A significant feature of this system is that phase errors result in colour errors in the reproduced picture.

PAL

This system developed in Germany closely resembles that of the NTSC. The significant difference is that the phase of the I signal is reversed during alternate lines. This reduces the colour distortion due to errors in phase introduced in the transmission system because a phase error in I modifies the reproduced colour in one direction whereas in the next line the same error modifies it in the other. The eye integrates the two lines and sees the mixture colour which is a slightly desaturated version of the original. In more elaborate PAL systems the integration is carried out electrically but this involves an extremely accurate delay line.

SECAM

The SECAM system like the NTSC system employs a luminance (Y) signal and two chrominance signals but the transmission system is quite different. In the SECAM system although the luminance signal is continuously transmitted the chrominance signals are transmitted sequentially, i.e. one chrominance signal is transmitted for one line, the other for the next line etc. As the receiver finally requires all three signals simultaneously, a delay circuit is required to delay the chrominance signal sent during one line by exactly the period of one line so that it may appear simultaneously with the chrominance signal transmitted in the next line.

The chrominance signals are frequency-modulated upon a sub-carrier at a multiple of the line scanning frequency and detected by a discriminator at the receiver. The output of the discriminator is switched electronically to direct one or other of the chrominance signals to the delay line.

In this system the bandwidths of the two chrominance signals ($R - Y$) and ($B - Y$) are necessarily the same so that advantage is not taken of the properties of the eye. It reduces vertical colour definition but this is already reduced horizontally by bandwidth reduction; it also avoids the need for a synchronous detector which is so susceptable to phase errors.

Conclusion

Whatever the system finally employed, the methods of colour analysis (at the studio) and synthesis (at the receiver) will continue to be determined by the principles of colorimetry already outlined.

The continuing need for compatibility will also require the employment in the transmission system of a luminance signal carrying all the brightness information and two chrominance signals carrying the required information about colour and saturation. These will be referred to in the next chapter as the transmission primaries.

How far the chrominance signals will be further modified to take maximum advantage of the eye's response to colour remain to be seen. At any rate it appears they will continue to be transmitted within the luminance band and so employ the persistance of vision to eliminate or considerably reduce the dot pattern caused by the sub-carrier.

5

COLOUR SPECIFICATION

Introduction

In this chapter we develop some of the ideas of colorimetry dealt with in chapters 3 and 4 beyond the minimum requirements needed for an understanding of colour television.

In particular we introduce the language of the International System of Colour Specification (C.I.E.*) which is so extensively used in literature on colour television.

C.I.E. System of Colour Specification

It was pointed out at the end of chapter 3 that the use of the trichromatic coefficients r and g to specify colour suffered from the disadvantage that complete specification required a knowledge of the measurement primaries and the chosen standard white.

These difficulties can be overcome for the purpose of international colour specification by defining the standard white and the measurement primaries as spectral colours having wavelengths as follows:—

Red	700·0 nm
Green	546·1 nm
Blue	435·8 nm

and standard white as equal-energy white.

These spectral measurement primaries lie on the spectrum locus but there remain areas enclosed by the spectrum locus which lie outside the *RGB* triangle. This means that a number of colours have negative trichromatic coefficients and the curves for the distribution coefficients (see Fig. 4.3) have negative-going loops. It was felt however, that international colour specification should avoid the use of negative coefficients and to avoid them the primaries required must be such that the triangle they form completely encloses the spectrum locus. In this way all real colours lie within the triangle. Unfortunately no three real primary colours can do this! Accordingly three non-real primary stimuli or super-saturated colours are chosen and referred to not as R, G, B but as X, Y, and Z.

Of course, any number of X, Y and Z triangles can be drawn to enclose the spectrum locus but good reasons exist for the one chosen.

*Commission Internationale d'Eclairage.

Once the positions of the three primary stimuli have been specified in terms of the measurement primaries *R*, *G* and *B* then any colour specified in terms of *R*, *G* and *B* can be specified in terms of *X*, *Y* and *Z*, and plotted on axes *y* and *x*. In this way the spectrum locus plotted on *r*, *g* axes can be replotted on *x*, *y* axes as shown in Fig. 5.1. Equal-energy white appears at $x = 0{\cdot}33$, $y = 0{\cdot}33$ as it is the standard white for the C.I.E. system. The positions of illuminants *A*, *B* and *C* are also indicated.

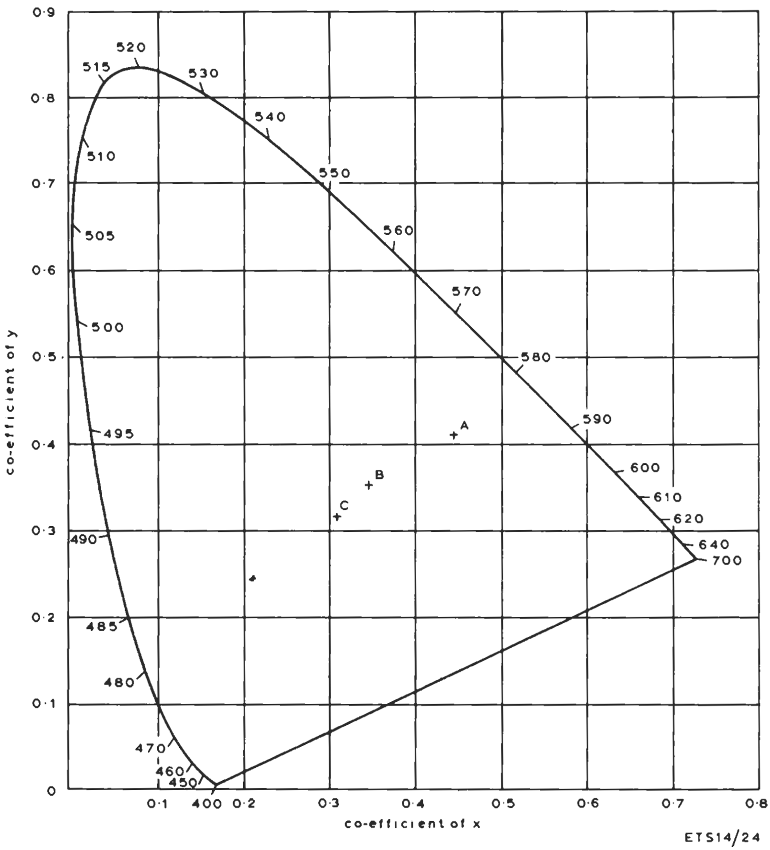


Fig. 5.1 C.I.E. trichromatic co-ordinates with points for illuminants A, B and C

Choice of X Y Z Triangle

A colour as we have seen has brightness and chrominance; the trichromatic coefficients *r*, *g* or *x*, *y* express the chrominance. In measurements involving

R, *G* and *B* primaries the total brightness of the matched colour is distributed amongst the primaries employed and we have seen how brightness can be calculated from a knowledge of the brightness of the primary T units. It would be extremely convenient if the brightness of a colour was entirely specified by the value of one only of the matching primaries. This can be done if the *X* and *Z* stimuli lie on the alychne, i.e. if they are colours of zero brightness. Under these conditions the *Y* stimulus entirely specifies the brightness and a

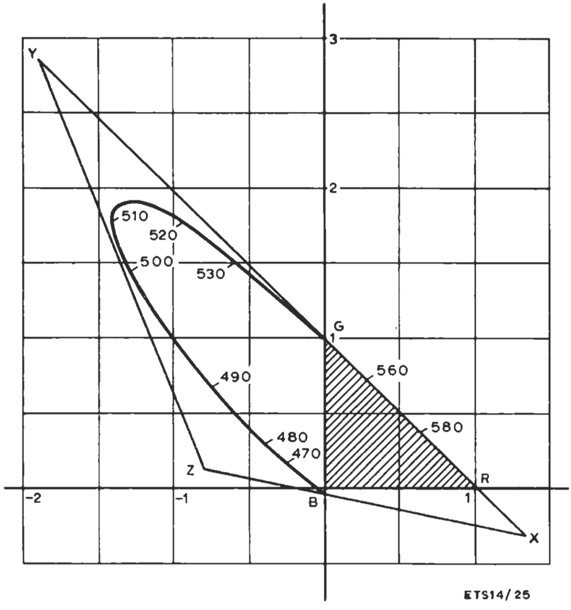


Fig. 5.2 Colour triangle in which one side coincides with the alychne

colour specified as

$$Y = 15 \text{ T units}$$
$$X = 5 \text{ T units}$$
$$Z = 5 \text{ T units}$$

has a brightness or luminance of 15 ft-lamberts and is located at the point

$$x = 5/25 = 0{\cdot}2$$
$$y = 15/25 = 0{\cdot}6$$

there being 25 T units of colour in the match.

Fig. 5.2 shows the *XZ* axis lying along the alychne. The position of this alychne differs from that shown in Fig. 3.3 because here we are using the international measurement primaries and equal-energy white as reference in place of the NTSC primaries and illuminant *C* used earlier.

The spectrum locus is almost a straight line from 540 nm to 700 nm and if the *YX* axis could lie along this line many spectral colours would require only *X* and *Y* values for their specification and this has considerable advantages in calculations. The line *YZ* is finally drawn to contain the spectrum locus.

The above is a simplified account of the reasons for the choice of the *X*, *Y*, *Z* stimuli.

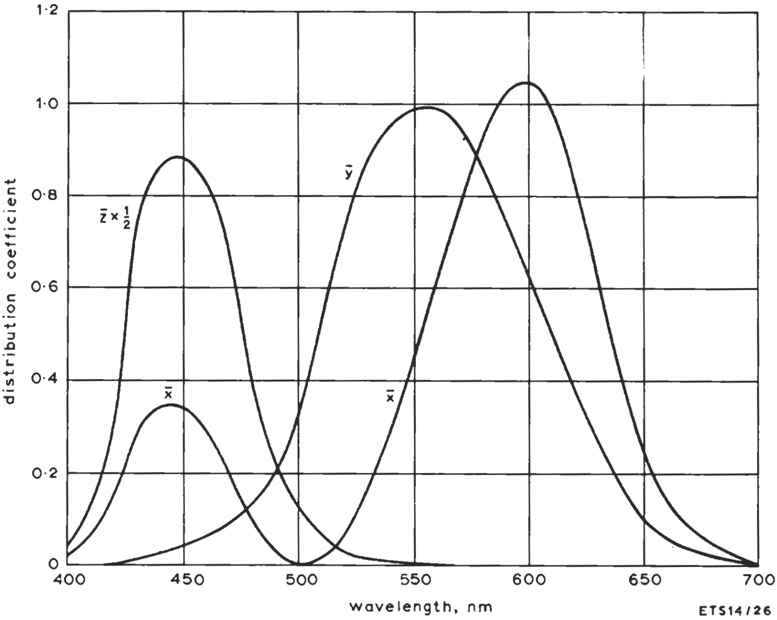


Fig. 5.3 $\bar{x}$, $\bar{y}$ *and* $\bar{z}$ *distribution coefficients*

Distribution Coefficients

Distribution coefficients $\bar{x}$, $\bar{y}$ and $\bar{z}$ can be plotted for the *X*, *Y*, *Z* stimuli as outlined in chapter 4. Equal-energy white is taken wavelength by wavelength and each monochromatic colour is matched by the measurement primaries *R*, *G*, *B*. These values are converted to $\bar{x}$, $\bar{y}$ and $\bar{z}$ values using the defined relationships between *X*, *Y*, *Z* and *R*, *G*, *B*. The curves obtained are shown in Fig. 5.3 and, as would be expected, they have no points below the horizontal axis. Another feature of the diagram is that the $\bar{y}$ curve has the shape of the average eye response, confirming that the *Y* stimulus represents the full brightness value of the colour.

Direct Measurement of X, Y, Z Values

The distribution curves Fig. 5.3 lead to a convenient method for the direct measurement of the tristimulus values of any given light. Filters are available having approximately these colour responses when used with photovoltaic cells. Three such cells equipped with $\bar{x}$, $\bar{y}$ and $\bar{z}$ filters respectively and each having a meter (Fig. 5.4) can be used. Calibration* is achieved by adjusting the meters to equal readings when the filter-photocell combinations are simultaneously illuminated with equal-energy white light. When the three filters are exposed to an unknown colour, the three readings give the X, Y, Z values, from which x and y can be found from the relationships

$$x = \frac{X}{X + Y + Z} \qquad y = \frac{Y}{X + Y + Z}$$

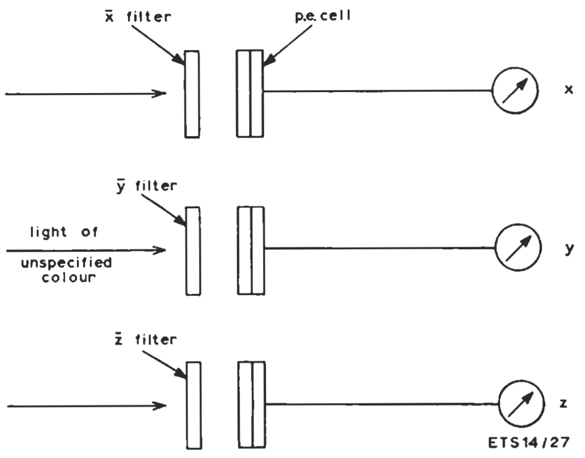


Fig. 5.4 Determination of the tristimulus values for light of an unknown colour

Three camera tubes equipped with $\bar{x}$, $\bar{y}$ and $\bar{z}$ filters and focused on a scene would produce outputs corresponding to a luminance signal Y and two chrominance signals X and Z corresponding to but not identical with $(R - Y)$ and $(B - Y)$, the zero-brightness transmission chrominance primaries. Such an arrangement would avoid matrixing the outputs of the tubes but the

*The Y filter and cell is the eye-response circuit mentioned in chapter 1 and the associated meter can be calibrated in lumens.

colour receiver would still need to extract the R, G and B signals. However the non-linearity of a practical colour television system and the consequent need for gamma correction make it more convenient to derive the R, G and B signals from the camera tubes.

Location of Transmission Primaries on the C.I.E. Diagram

The transmission primaries Y, $(R - Y)$ and $(B - Y)$ can be located as colour points on the C.I.E. diagram.

In the absence of $(R - Y)$ and $(B - Y)$ the received picture is white and the Y primary is represented by the white point in the C.I.E. diagram. $(R - Y)$ and $(B - Y)$ contain no brightness information and must therefore lie on the x axis, where $y = 0$. The x axis is the alychne. When $Y = 0$ and $(R - Y) = 0$ the colour transmitted must be $(B - Y)$. Now if $Y = 0$ then $R = 0$ and this is so for all points on the GB line of the colour triangle. Along this line all colours are simple mixtures of G and B, R being zero. This extension of the side GB of the RGB triangle (colour receiver phosphor colours) to cut the x axis ($Y = 0$) gives the point corresponding to the colour $(B - Y)$. Similarly $(R - Y)$ is obtained by extending the line GR to cut the x axis as shown in Fig. 5.5. In a similar way given the relationship of the I and Q signals to the R, G, B primaries the colour points I and Q can be plotted, again on the alychne. The colour triangle YIQ represents the transmission primary triangle. Negative values of I and Q are possible so that colours outside the YIQ triangle can be transmitted. The side YI intercepts the RGB triangle in orange and cyan so that in the absence of a Q signal colours transmitted lie between orange and cyan. Similarly the side YQ intercepts the RGB triangle in green and magenta. Indeed the I and Q colour points could have been determined by the intersections of the orange-cyan line and the green-magenta line with the x axis respectively.

Mixture of Colours on the C.I.E. Diagram

The C.I.E. diagram can be used to determine what colours are produced when two given colours are added. Suppose the two colours are represented by C_1 (0·2, 0·4) and C_2 (0·6, 0·3) on the C.I.E. diagram of Fig. 5.6. Suppose too, that the colours are added in the proportions of 18 lumens of C_1 and 25 lumens of C_2. The C.I.E. diagram in common with previous chromaticity diagrams is concerned with only 1 T unit of each colour involved, i.e.

$$1(C_1) \equiv 0{\cdot}2(X) + 0{\cdot}4(Y) + 0{\cdot}4(Z)$$
$$1(C_2) \equiv 0{\cdot}6(X) + 0{\cdot}3(Y) + 0{\cdot}1(Z)$$

The number of lumens of each colour automatically gives the Y value of

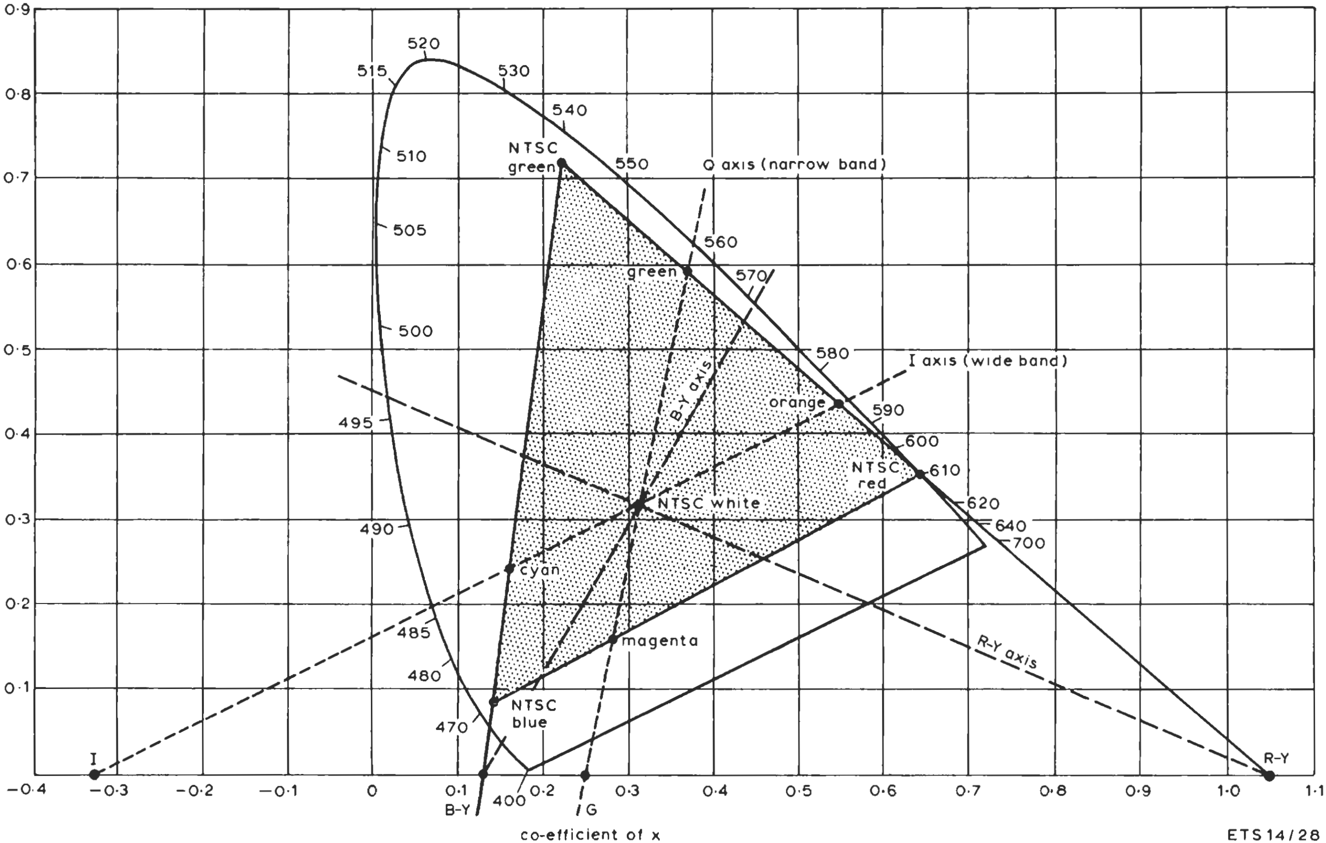


Fig. 5.5 Location of colour television transmission primaries on C.I.E. diagram

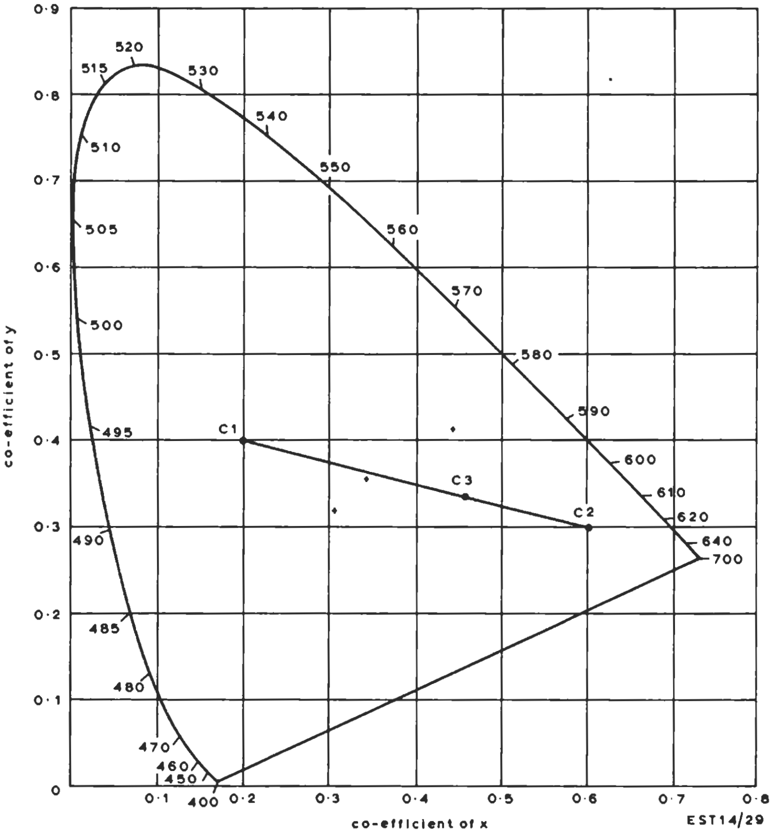


Fig. 5.6 Representation of mixture colour on C.I.E. diagram

each and

$$y = \frac{Y}{X + Y + Z}$$

so that for colour C_1

$$0{\cdot}4 = \frac{18}{X + Y + Z}$$

Thus $$X + Y + Z = 18/0{\cdot}4 = 45 \text{ T units}$$

Now $$x = \frac{X}{45}$$

$$\therefore X = 9$$

and $$z = \frac{Z}{45}$$

$$\therefore Z = 18$$

Thus $$45(C_1) \equiv 9(X) + 18(Y) + 18(Z)$$

In the same way we can show that

$$83(C_2) \equiv 49{\cdot}7(X) + 25(Y) + 8{\cdot}3(Z)$$

The mixture colour is obtained by adding the X, Y and Z values to obtain

$$128(\mathrm{C}_3) \equiv 58{\cdot}7(X) + 43(Y) + 26{\cdot}3(Z)$$

and hence $$x = \frac{58{\cdot}7}{128} = 0{\cdot}46 \text{ approx.}$$

and $$y = \frac{43}{128} = 0{\cdot}34 \text{ approx.}$$

Thus the colour obtained by mixing 18 lumens of C_1 with 25 lumens of C_2 is C_3 situated at $x = 0{\cdot}46$ and $y = 0{\cdot}34$. This point lies, as it must, on the line joining C_1C_2 as shown in Fig. 5.6.

An easier geometrical method of obtaining this result is illustrated in Fig. 5.7. Find the number of T units of each colour as before, i.e. 45 T units of C_1 and 83 of C_2. On a horizontal line through C_1 mark off to the right a distance C_1A corresponding to 83 T units, say 8·3 cm. Similarly on a horizontal line through C_2 mark off a distance BC_2 to the left corresponding to 45 T units, say 4·5 cm. AB intersects the line C_1C_2 at the colour mixture point C_3. All we have done in fact is to divide C_1C_2 in the ratio 83/45 by a standard geometrical procedure.

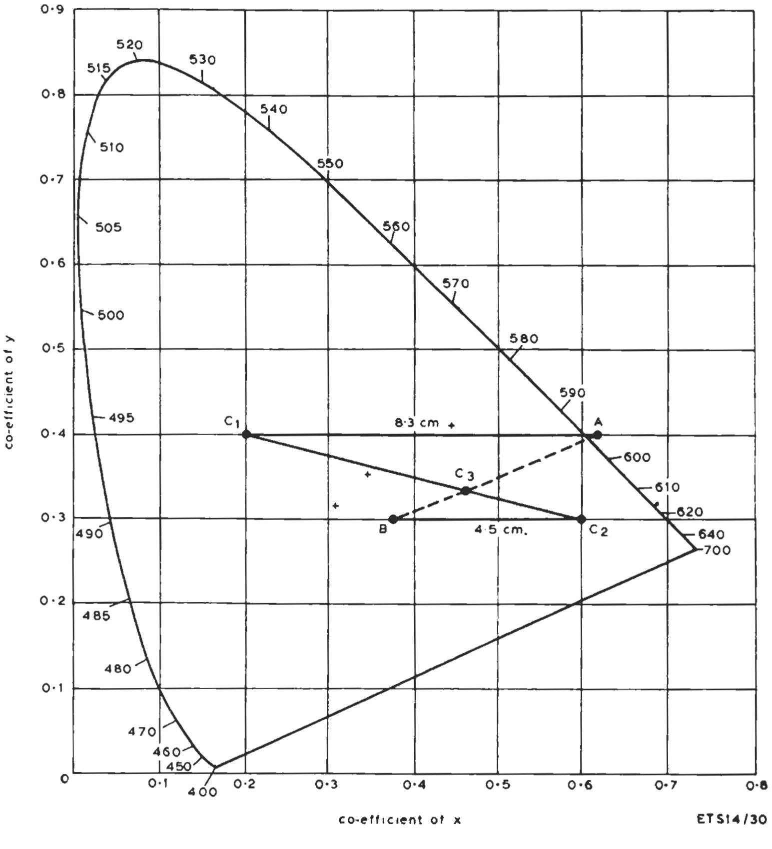


Fig. 5.7 Geometrical construction for determining the colour (C_3) produced when 18 units of colour C_1 are added to 25 units of C_2

Conclusion

The location of transmission primaries on the C.I.E. diagram and the calculation of colour mixture serve as examples of application of the X, Y, Z tristimulus system and show its practical value. The reader should now be in a position to read further in the field of colorimetry generally or its specific application to colour television. To this end a list of recommended books is given.

H.H. 5/64

BIBLIOGRAPHY

	Title	*Author*	*Publisher*
1	An Introduction to Colour	R. Evans	Wiley
2	The Measurement of Colour	W. D. Wright	Hilger and Watts
3	The C.I.E. International Colour System Explained	G. J. Chamberlin	Tintometer
4	Colour Television: The N.T.S.C. System Principles and Practice	P. S. Carnt and G. B. Townsend	Iliffe