Methods of measurement of the colorimetric performance of studio monitors

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Introduction

For the purposes of specifying and assessing the colorimetric performance of a television picture monitor, it is necessary to measure the following parameters:

- The chromaticities of the primary red (*R*), green (*G*), and blue (*B*) light emissions.
- The white uniformity over the picture area.
- The transfer characteristics (gamma, γ).
- The achievable contrast.

Picture monitor emissions are controlled by the *R, G, B* signal voltages applied to the drive amplifiers, and measurements of the television signal processing system, and of the scanning standard, can therefore be made independently.

The specification and tolerance for the primaries has been defined in EBU document Tech. 3213 [1]. At the time of publication of this standard, only a few laboratories were able to carry out such measurements with the required precision. More recently economic commercial equipment has become available and it now seems appropriate to give guidelines for measurement procedures.

The techniques described in this document can be applied equally to conventional television displays with either 4:3 or 16:9 aspect ratio, and to HDTV displays.

List of symbols

Colorimetric symbols

λ	Wavelength, nm.
P_λ	Spectral power distribution (radiance) of a light source.
$\bar{x}, \bar{y}, \bar{z}$	Spectral colour matching functions for a Standard 2° Observer in the CIE 1931 colour system.
D_{65}	Standard white point for television systems.

The following symbols may be used with suffices as follows:

- *s* : test colour source values.
- *d* : test colour display values.
- *r* : red primary values.
- *g* : green primary values.
- *b* : blue primary values.
- *o* : values for D_{65} reference white.

X, Y, Z	Tristimulus values for CIE 1931 colour system.
u', v'	Chromaticity coordinates for CIE 1976 chromaticity diagram.
x, y	Chromaticity coordinates for CIE1931 chromaticity diagram.
R, G, B	Display drive voltages.
L^*, C^*	CIELuv colorimetric values.
$\Delta L^*, \Delta C^*, \Delta E^*$	CIELuv colorimetric differences.

Physical properties of the display

H	Height of display picture area.
W	Width of display picture area.
L	Luminance level of display.
L_{min}	Luminance level of black setting of display.
L_{max}	Peak luminance level of the display.
l_o	Offset in light level when making transfer characteristic measurements, due to black level errors, stray light, dark current in detector.
V	Drive voltage applied to display, to cause illumination level L.
V_{grey}	Drive voltage applied to display, to cause an illumination level which is precisely 50% of L_{max}.
V_{max}	Drive voltage applied to display, to cause illumination level L_{max}.
v_o	Offset in drive voltage when making transfer characteristic measurements, causes black level error.
γ	Power law describing display transfer function, gamma.
C	Contrast of the display.
F	Flare of the display.

Chapter 1

Measurement of chromaticity

The measurement of the chromaticity of a light source is a standard colorimetric procedure and a number of methods have been developed. It is sufficient to select suitable methods that can be applied to the particular characteristics of a picture monitor which has a discontinuous light output by reason of the scanning process and the nature of the spectral and temporal characteristics of the phosphor or other light source.

Two methods have been established which give similar results; the spectroradiometric method, and the tristimulus method. *Fig. 1* indicates the process of measurement and computation, and the detailed procedures for measurement, computation and presentation follow.

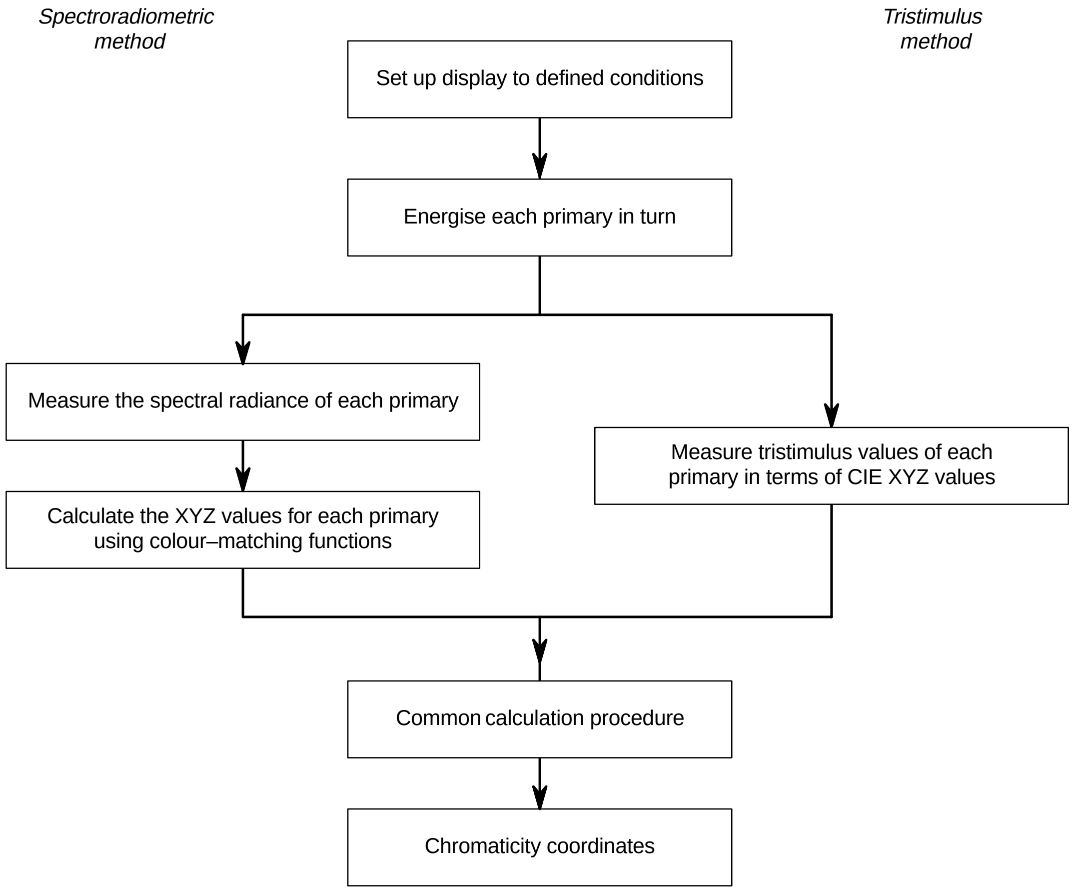


Fig. 1 – The two measurement methods with common calculation procedure.

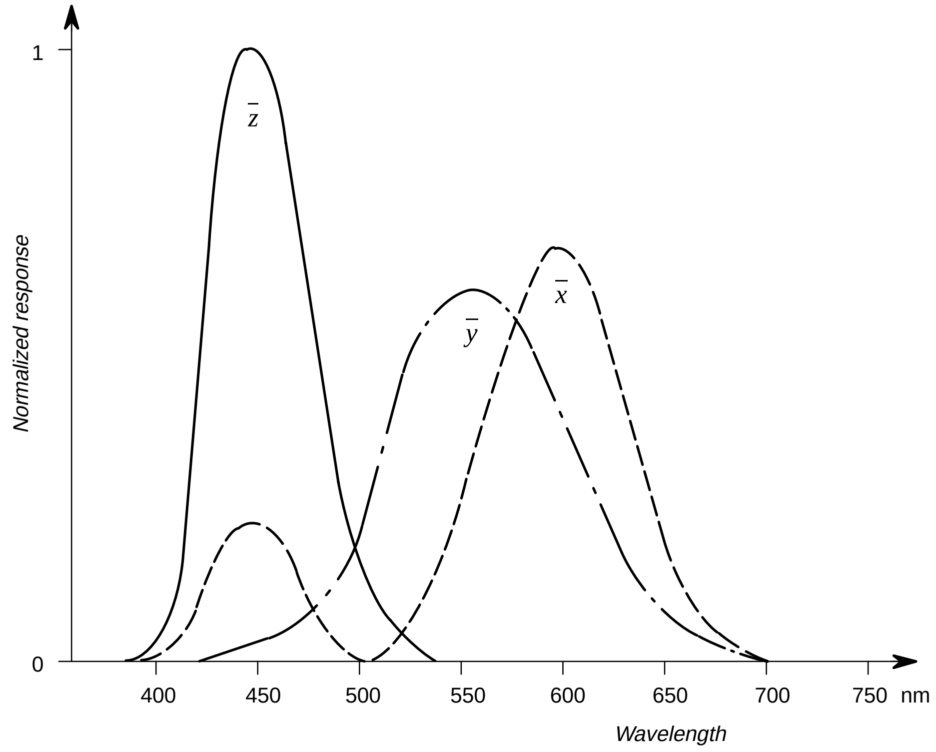


Fig. 2 – The colour matching functions (1931 2° Standard Observer).

1.1. Suitable measuring techniques

All techniques involve measuring, wavelength by wavelength (λ), the light energy coming from the monitor. The spectral power distribution thus obtained (P_λ), may be converted to tristimulus values by multiplying it by each of the colour matching functions ($\bar{x}$, $\bar{y}$, $\bar{z}$) in turn and integrating the resultant curves. Chromaticity coordinates may then be obtained by normalisation.

The colour matching functions, representing the amount of each CIE XYZ primary required to match the individual wavelengths in the colour under test are shown in *Fig. 2*. They are the results of measurement of the colour vision of a number of observers before 1931 by Wright and others and were accepted by the CIE as the definition of the CIE 2° Standard Observer; they are thus uniquely defined and provide the only basis for an objective measurement system.

Two methods of measurement are described; a spectroradiometric method by which the spectrum is measured wavelength by wavelength, and a tristimulus method which directly yields the tristimulus values and chromaticity coordinates.

An alternative method uses a tristimulus meter in which the total light energy from the monitor is modified using filters designed to replicate each of the colour matching functions to give the tristimulus values directly.

The relative advantages and disadvantages of these two techniques are considered in more detail in *Sections 1.2.* and *1.3.*

1.2. Spectroradiometry

Spectroradiometric equipment comprises a means of measuring the light energy, wavelength by wavelength, across the whole spectral range and a data processor which calculates the tristimulus values by multiplication of this spectrum with the colour matching functions and then integration. Thus, provided that the bandwidth of the wavelength scanning device is accurately controlled, and its gain characteristic is known, accurate results are obtained.

Two spectroradiometric methods are now available; simultaneous measurement using a spectrum splitter and an assigned sensing cell for each wavelength, and wavelength scanning where one sensing cell is used at the output of a scanning spectrum splitter (monochromator). Either method will produce the spectral radiance, P_λ , of the colour. This should be measured over the visual part of the spectrum; 380 to 760 nm is a typical range. The instrument's calibration must be traceable to a standards bureau. Tristimulus values are then derived by multiplication and integration as described above, using data values of the appropriate colour matching functions tabulated by the CIE:

$$X = \int_{380}^{760} P_\lambda . \bar{x}_\lambda . d\lambda \qquad Y = \int_{380}^{760} P_\lambda . \bar{y}_\lambda . d\lambda \qquad Z = \int_{380}^{760} P_\lambda . \bar{z}_\lambda . d\lambda$$

1.3. Tristimulus meter

This equipment usually comprises three light sensitive cells, with spectral sensitivities modified by filters to mimic the colour matching functions ($\bar{x}, \bar{y}, \bar{z}$). Thus the electrical outputs of the cells give a direct reading of the tristimulus values (X, Y, Z) of the test colour, from which the chromaticity coordinates can be calculated. Clearly, it is essential that the cell responsivities precisely match the colour matching functions, and that the instrument should be calibrated by measurement of a standard white source and some typical colour primaries. This calibration should be traceable to a standards bureau.

The merit of the tristimulus meter is that it can be a small, hand–held device which produces instant readings. Its disadvantage is that its accuracy depends, to some extent, on the smoothness of the spectrum it is measuring. With a smooth spectrum, small errors in the cell responsivities are of little significance, but with light sources whose spectra do not vary smoothly, such as rare–earth phosphors and discharge lamps, the light energy may be in the form of a small number of narrow–band peaks occurring at wavelengths where even small filter errors can produce inaccurate tristimulus values.

1.4. Measurement conditions

The measurement conditions, and precautions that should be considered when making measurements, are similar for all photometric measurements on studio monitors and these are listed in *Chapter 4*.

1.5. Measurement procedure

The monitor should be driven with a peak white, 700mV amplitude, signal. A single illuminated area of the display can be used, provided that it fully illuminates the measuring instrument. For convenience, a signal illuminating more than one area can be used such as that for white uniformity measurements. The light level should be adjusted to luminance value of 80 cd/m^2 using a calibrated photometer (luminance meter) as specified in EBU Technical Recommendation R23 [2].

Measurements are made for each primary by switching off the other two primary emissions, for example, cathode–ray tube guns. It is essential that the drive for emissions from the other two primaries is completely suppressed although low level emissions may be measured due to flare and other factors. Measurement should be made at the centre of the screen where unwanted emissions will be minimum.

Spectral power distribution or tristimulus values should be recorded for each primary together with type and serial number of the cathode–ray tube and monitor.

Procedures for calculating the primary chromaticity coordinates and the subsequent computations for establishing the coordinates of specific test colours are outlined in *Chapter 5*. The results of the measurements should be presented as shown in *Chapter 6*.

Chapter 2

Measurements of white uniformity

2.1. Definition of white uniformity

White uniformity is defined as the evenness of light output and chromaticity over the picture area. In cathode–ray tubes, imperfect white uniformity is generally a combination of several effects; beam landing errors in which electrons aimed at one colour phosphor partially hit others, variations in the shadow mask, variations in glass thickness and composition, variations in phosphor composition.

2.2. Measurement conditions

The measurement conditions, and precautions that should be considered when making measurements, are similar for all photometric measurements on studio monitors and these are listed in *Chapter 4*.

2.3. Measurement procedure

Measurements are made at nine standardised positions within the screen area defined in terms of screen height and width, these are indicated in *Fig. 3*.

Measuring point	**Coordinates** (relative to screen centre)	
	w	***h***
1 (screen centre)	0	0
2 and 4	0	±0.4H
3 and 5	±0.4H	0
6, 7, 8 and 9	±0.4W	±0.4H

The area of measurement should not be greater than a circle of diameter 0.1 H.

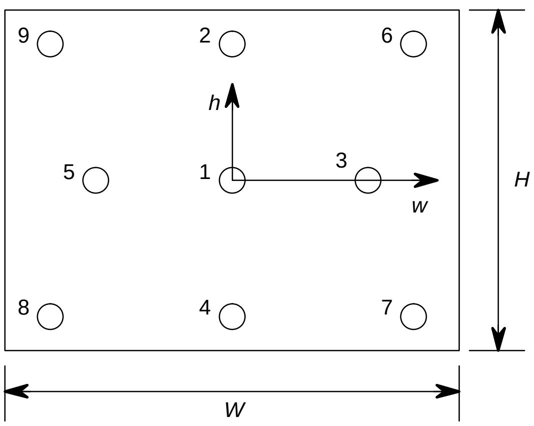


Fig. 3 – Measurement points for the measurement of white uniformity.

The display should be driven with a peak white, 700mV amplitude, video signal. A suitable signal is one which illuminates the nine measurement areas and, for simplicity, can comprise nine square white patches of 0.15H dimension centred on the measuring points, the remaining area to be black. The brightness, contrast, white balance and black balance should be adjusted according to EBU Technical Recommendation R 23 [2]. The light level at the centre of the screen should then be 80 cd/m^2.

The CIE 1976 colorimetric coordinates *Y, u', and v'* [3] for the white emission are required at each of the nine positions. Spectroradiometry or tristimulus meter methods as described in *Chapter 1* can be used for the measurements from which the *Y, u', v'* coordinates can be obtained by computation. Use of the tristimulus meter method will usually be quicker and simpler than the spectroradiometric method.

Measurements are first made at the centre of the screen; this gives a further check on white balance which should be close to D_{65} since this central position acts as reference for the remaining measurements. Measurements should then be made at the remaining eight positions.

The type and serial number of the cathode–ray tube and monitor should be recorded, together with any supplementary comments or measurements if found necessary.

The results of the measurements should be presented as shown in *Chapter 6*.

Chapter 3

Measurement of transfer characteristics and contrast

3.1. Isolation of the display device transfer characteristic

In a cathode–ray tube or other display device, the transfer function is defined by the relationship between electrical signal and emitted light. It is necessary to know as precisely as possible this transfer function which may not be linear. When viewing a display, the observed transfer characteristic is modified by a number of factors, the setting of black level, the level of output illumination, and the level of ambient illumination. For the specification of monitor performance it is the display device transfer characteristic only that is required and so uncontrolled effects must be excluded.

3.2. Measurement conditions

The measurement conditions, and precautions that should be considered when making measurements, are similar for all photometric measurements on studio monitors and these are listed in *Chapter 4*.

For measurement of transfer characteristic, particular care should be taken in adjusting white balance and grey scale tracking.

3.3. Transfer characteristic measurement procedure – objective analytical method

The monitor should be driven with a peak white, 700mV amplitude, signal, for example that defined for the measurement of white uniformity. The light level should be adjusted to luminance value of 80 cd/m^2 using a calibrated photometer (luminance meter) as specified in EBU Technical Recommendation R23 [2].

When measuring transfer characteristic it is required to measure the light output level over the complete range of drive signal from 0mV to 700mV as set by a calibrated attenuator connected to the monitor input. To ensure that this condition is satisfied, the brightness of the display should be adjusted, with an input signal of 0mV, to be only just above "cut–off". However, the actual luminance level (L_{min}) should be capable of accurate measurement using a calibrated photometer and this may necessitate raising the brightness further. In any case the brightness should be not greater that 0.5 cd/m^2; in this manner the transfer characteristic can be measured for a luminance ratio of at least 160:1. Although the procedure of setting the monitor above "cut–off" will modify the measured transfer characteristic, the effect can be allowed for in subsequent computations.

The brightness and contrast settings of the monitor must not be altered during the course of measurement.

The transfer characteristic is established by a series of measurements of display brightness versus drive voltage. The input video signal (V) is varied logarithmically between 0–700mV using a calibrated attenuator and the luminance level (L) is measured and recorded for each step using a calibrated photometer.

The transfer function is characterised by:

$$\gamma = \frac{log(L/L_{max})}{log(V/V_{max})}$$

which is the slope of the straight line running through the points plotted logarithmically. As mentioned previously, this definition assumes that for V = 0mV, luminance is zero and not the measurable value as preset above, and also that a valid power–law relationship exists. Allowance for the non–zero black level setting is outlined in *Chapter 5*, and the results of the measurements should be presented as shown in *Chapter 6*.

3.4. Transfer characteristic measurement procedure – flicker photometric method.

It may be desirable to make visual assessment of the transfer characteristic of a picture monitor under operational conditions, for example to check that two adjacent monitors have the same characteristics. A method exists for subjectively assessing the value of γ at mid–grey. A test signal for such a method could be one which comprises one field of a uniform mid–grey, and the second field has alternate lines of black and white. This signal will produce picture–rate flicker which can be minimised by adjustment of V_{grey}, at which point the two fields have the same subjective brightness. For a cathode–ray tube display, the transfer function can then be characterised by:

$$\gamma = \frac{log(0.5)}{log(V_{grey}/V_{max})}$$

which is the slope of the logarithmic straight line running through black, mid–grey, and white. This also assumes the same limitations as for the objective measurements. The value of γ is an indication of the true value of gamma at mid–grey only; it may not be fully representative of the display over the entire grey scale range.

For simplicity a test signal comprising several test patches can be used, each patch with alternate black and white lines on one field and mid–grey processed by different values of γ on the other. *Fig. 4.* shows the layout of such a test signal [4] which contains ten test patches; it also has a peak white (100% = 700mV) patch for setting contrast and two low amplitude (±2% = ±14mV) bars centred upon black level for setting brightness. When using this test signal, the correct value of γ for the display is the one which was used to prepare the patch which exhibits minimum flicker at picture rate.

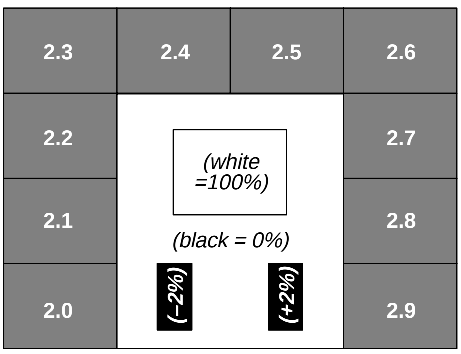


Fig. 4 – Test signal for flicker–photometric measurement of gamma.

A photometer can be used to establish which patch produces the condition of minimum picture–rate flicker more accurately than can be done by eye. A filter of about 1ms time constant is needed to remove all line–frequency components. The output of the photometer is viewed on an oscilloscope scanning at field rate, the picture–rate flicker is minimum when the amplitudes of the signals in the two fields are the same, and the patch which produces that condition indicates the γ of the display.

Values of mid–grey at various values of γ are tabulated in *Chapter 5*.

3.5. Contrast measurement procedure

The contrast of a display can be defined as follows:

$$C = \frac{L_{max}}{L_{min}}$$

where L_{max} is the luminance reproduced with a 700 mV signal and L_{min} that reproduced with no signal (0 mV). Assuming that black level has been set correctly, then in a darkened room L_{min} will be zero with no signal and hence contrast will be infinite. In the presence of ambient lighting or inaccurately set black level, L_{min} will be non–zero and dependant upon the measurement conditions, thus giving rise to a wide range of values for contrast.

Clearly, the use of separate white and black signals for the measurement of L_{max} and L_{min} can result in many different values for contrast, and therefore contrast must be calculated using measurements of white and black from within only one test picture. The contrast thus derived will contain an element of flare due to the presence of peak white and, again, the result will depend on the nature of the test signal and the manner in which the display was set up. The display black and white levels must be set using a standard PLUGE signal such as that specified in CCIR Recommendation 814 [4].

A suitable test signal for contrast measurement is that specified in CCIR Recommendation 815 [5] and consists of a peak white level patch surrounded by four black level patches, all set against a background of grey which is at 50% of the peak signal. The layout of the test signal is shown in *Fig. 5*.

Measuring point	**Coordinates** (relative to screen centre)	
	w	***h***
1 (white)	0	0
2 and 4 (black)	0	±H/3
3 and 5 (black)	±H/3	0

Each patch is a square of dimension H/7.5 (13.13% of H).

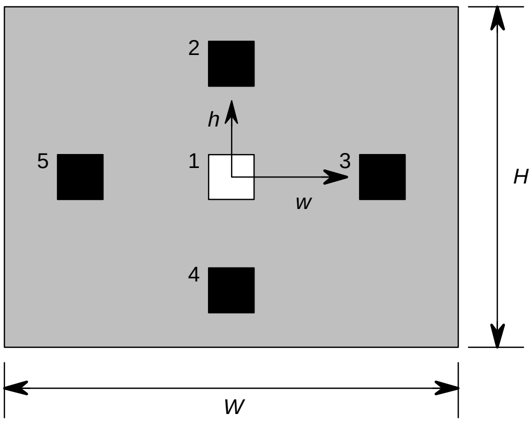


Fig. 5 – Test signal for contrast measurement.

The black level L_{min} should be the mean of measurements made of the four black patches, the white level L_{max} should be measured in the central white patch. The resulting value for contrast thus contains a flare element and can be used only for purposes of comparison between displays.

Chapter 4

Measurement conditions and precautions

4.1. Measurement conditions

To ensure absolute and repeatable measurements, the following conditions should be observed:

– Measurements should be made in a darkened room.

– The display should be placed away from surfaces which might reflect light into the measuring equipment.

– Equipment indicator lamps etc. should be shielded from the measuring equipment.

– Cathode–ray tube displays are affected by magnetic fields and so should be placed such that the effects of any magnetic field is minimised.

– The cathode–ray tube display ideally should be degaussed with an external coil. If this is not possible, the internal degaussing coil must be used.

– The monitor must be allowed to warm up for 3/4 hour while displaying a grey signal which gives a luminance of $15cd/m^2$.

– Displays should be checked for adjustment of purity, scan size and linearity, convergence, focus, grey–scale tracking, and achieved white colour temperature for D_{65} following the procedures specified in EBU Technical Recommendation R23 [2]. If the adjustment is in error, corrections must be made where possible, according to the manufacturer's procedures.

– During measurements, cathode–ray tube displays must not be subjected to long–term high–level full–field signals which might cause mask heating and consequent distortion.

– Any colour correction matrices must be switched off.

4.2. Measurement precautions

There are several precautions that should be considered. These relate mainly to the characteristics of the measuring equipment used.

– The instrument optical axis should be normal to the surface of the display. Small deviations are probably not significant since most detectors use integrating apertures or diffusers.

– The instrument entrance aperture should be fully illuminated to prevent uneven illumination of the sensor(s).

– The detector temporal performance must be linear. Due to the scanning nature of television, and the limited area of measurement, the detector is not continuously illuminated. The temporal performance and integration characteristics must be linear and peak excitation must not cause overloading.

– The detector must be linear, or be accurately corrected to be linear. This is to ensure correct integration of peak and afterglow excitation. Auto–ranging detectors must not overload before range–changing. These factors should be checked at more than one wavelength to allow for different afterglow performance at different wavelengths.

– Spectroradiometer slit and incremental wavelength must match each other. The slit widths define the effective "bandwidth" and aperture shape of the radiometer, these must match the incremental wavelength in order to resolve spectral emissions optimally. A pre–run should be performed to determine peak response and to ensure that overloading does not occur.

– Noise and zero levels should be checked. Detector sensitivity should be such that noise levels are not significant. Extraneous light can contribute to noise in the detected signal. Zero levels can be affected by electrical offsets and detector dark–current, these should be allowed for.

Chapter 5

Calculation procedures

5.1. Chromaticity calculations

Chromaticity coordinates in the CEI 1931 colour space can be obtained, for each primary, from the tristimulus values:

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

The third coordinate, z, is not required since $x + y + z = 1$. For television purposes, it is more customary to use coordinates in the CIE 1976 colour space, derived either by transformation from x and y or, more–directly, from the tristimulus values:

$$u' = \frac{4x}{-2x + 12y + 3} = \frac{4X}{X + 15Y + 3Z} \qquad v' = \frac{9y}{-2x + 12y + 3} = \frac{9Y}{X + 15Y + 3Z}$$

The *u'v'* coordinates can be plotted directly on a chromaticity diagram as shown in *Fig. 6.*, and the results presented as shown in *Chapter 6*.

The three quadrilaterals shown in the CIE 1976 *u'v' (Fig. 6)*, define the tolerances allowed for each of the three primaries. The exact coordinates of each corner of the tolerance quadrilaterals are listed in the table at the bottom of *Fig. 6*.

For the calculation of colour reproduction errors and the presentation of white–uniformity results, these coordinates should also be transformed into CIELuv units. This system is preferred because it more–closely relates objective measurements to subjective experience. The units are:

$$L^* = 116(Y/Y_o)^{1/3} - 16$$

$$u^* = 13L^*(u' - u'_o) \qquad v^* = 13L^*(v' - v'_o)$$

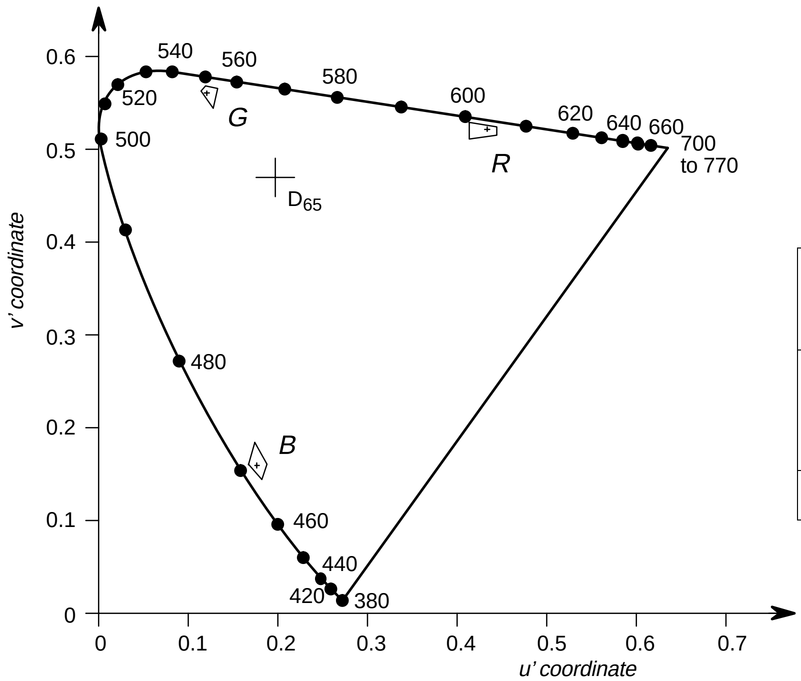
where: $Y_o = 1$,
$u'_o = 0.1978$,
$v'_o = 0.4683$
these being the values for the television system white point, D_{65}.

A further value C^* can be derived, this being the correlate of subjective chroma; it is similar to television saturation:

$$C^* = (u^{*2} + v^{*2})^{1/2}$$

The results should be given in difference units, for example:

$$\Delta L^* = L^*_d - L^*_s$$



Primary	Coordinates	
	u'	v'
Red	0.451	0.524
Green	0.121	0.561
Blue	0.175	0.158
D_{65}	0.1978	0.4683

Primary	Coordinates of corners of tolerance quadrilaterals							
	u'_1	v'_1	u'_2	v'_2	u'_3	v'_3	u'_4	v'_4
Red	0.461	0.527	0.461	0.518	0.431	0.513	0.431	0.531
Green	0.113	0.566	0.128	0.545	0.115	0.563	0.120	0.569
Blue	0.186	0.159	0.180	0.143	0.166	0.159	0.173	0.183

Fig. 6 – Intrinsic chromaticity tolerances for the standardised primaries.

5.2. Test colour reproduction

Having found the chromaticity coordinates of the three primaries (x_r y_r), (x_g y_g), and (x_b y_b), and also (u'_r v'_r), (u'_g v'_g) and (u'_b v'_b), it is useful to calculate the appearance of some test colours. For the purpose of these calculations it is assumed that the overall transfer characteristic is linear. A graphical method is described in EBU document Tech. 3213 [1], but this is only suitable for one defined skin tone (Y = 0.4404, u' = 0.2221, v' = 0.4884). A more rigorous technique is described below.

A test colour, defined by its luminance value Y_S and CIE 1976 coordinates u'_S v'_S, is transformed to the ideal drive voltages R_S, G_S, and B_S, as follows:

$$x_s = \frac{9u'_s}{6u'_s - 16v'_s + 12} \qquad y_s = \frac{4v'_s}{6u'_s - 16v'_s + 12} \qquad z_s = 1 - x_s - y_s$$

from which the tristimulus values can be derived:

$$X_s = \frac{x_s Y_s}{y_s} \qquad Z_s = \frac{z_s Y_s}{y_s}$$

and then the drive signals for an ideal EBU display are given by:

$$\begin{bmatrix} R_s \\ G_s \\ B_s \end{bmatrix} = \begin{bmatrix} 3.0627 & -1.3928 & -0.4759 \\ -0.9689 & 1.8756 & 0.0417 \\ 0.0677 & -0.2286 & 1.0690 \end{bmatrix} \cdot \begin{bmatrix} X_s \\ Y_s \\ Z_s \end{bmatrix}$$

To calculate the coordinates of this test colour as displayed on the monitor in question, it is necessary to calculate the synthesis matrix which converts the ideal drive voltages R_S, G_S, and B_S, to the displayed tristimulus values X_d, Y_d, and Z_d. The generalised procedure is as follows, and is described in detail in [7]:

The tristimulus values for a colour *n* are obtained using its *R*, *G* and *B* values:

$$\begin{bmatrix} X_s \\ Y_s \\ Z_s \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix} \cdot \begin{bmatrix} R_n \\ G_n \\ B_n \end{bmatrix}$$

This uses the *X, Y, Z,* tristimulus values of the primaries, which can be derived from the measured primary chromaticities by balancing them to D_{65} (subscript o):

$$\begin{bmatrix} X_o \\ Y_o \\ Z_o \end{bmatrix} = \begin{bmatrix} x_r & x_g & x_b \\ y_r & y_g & y_b \\ z_r & z_g & z_b \end{bmatrix} \cdot \begin{bmatrix} a_r \\ a_g \\ a_b \end{bmatrix}$$

where the “a” matrix gives multiplying factors for the primaries. This equation can be solved since the tristimulus matrix on the left–hand side of the equation is that of the white point, D_{65}, thus:

$$\begin{bmatrix} X_o \\ Y_o \\ Z_o \end{bmatrix} = \begin{bmatrix} x_o / y_o \\ 1 \\ z_o / y_o \end{bmatrix}$$

and by definition:

$$R_o = G_o = B_o = 1$$

Now the “a” matrix can be found by matrix inversion:

$$\begin{bmatrix} a_r \\ a_g \\ a_b \end{bmatrix} = \begin{bmatrix} x_r & x_g & x_b \\ y_r & y_g & y_b \\ z_r & z_g & z_b \end{bmatrix}^{-1} \cdot \begin{bmatrix} x_o / y_o \\ 1 \\ z_o / y_o \end{bmatrix}$$

and the “a” values can then be substituted into the tristimulus equation to produce the analysis matrix by multiplying each chromaticity coordinate by the appropriate “a” factor. This tristimulus matrix can then be used for colour analysis.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} a_r x_r & a_g x_g & a_b x_b \\ a_r y_r & a_g y_g & a_b y_b \\ a_r z_r & a_g z_g & a_b z_b \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Finally the display coordinates (subscript d) of the test colour can be calculated using the primary analysis matrix derived above, thus the tristimulus values are:

$$\begin{bmatrix} X_d \\ Y_d \\ Z_d \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix} \cdot \begin{bmatrix} R_s \\ G_s \\ B_s \end{bmatrix}$$

from which the CIE 1976 chromaticity coordinates can be calculated:

$$u'_d = \frac{4X_d}{X_d + 15Y_d + 3Z_d} \qquad v'_d = \frac{9Y_d}{X_d + 15Y_d + 3Z_d}$$

These are then the final display coordinates of the test colour.

If a comparison with the previous graphical method is required, the same defined skin tone should be used, otherwise any test colour or set of colours can be used.

5.3. Transfer characteristic calculations – objective analytical method

Measurements can be plotted directly onto a logarithmic graph to obtain a value of γ found by inspection of the slope of the linear part; this is prone to errors resulting from the non–zero setting of black level and from stray light or dark current in the detector. The slope through the linear part may not provide an accurate value for γ. These problems are overcome by adopting a differential calculation process, the method has been described in full [8]. Briefly, it is assumed that the transfer characteristic is:

$$L + l_o = k(V + v_o)^{\gamma}$$

where l_o and v_o are offsets in light and drive. Differentiating this produces:

$$\frac{dL}{dV} = k'(V + v_o)^{(\gamma - 1)}$$

Thus on a logarithmic plot of *dL/dV* versus *V*, the slope of the line through all points is $\gamma - 1$ and so γ = slope+1.

If v_o (the error in setting black level) is non–zero, then there will be curvature on the data points about the γ line on the differential plot. The curvature can be removed by estimating a value for v_o, which is best done using a computer optimisation routine, such as is given in *Appendix 1*.

Similarly, v_o can be eliminated from the calculation:

$$\frac{dL}{dV} = k''(L + l_o)^{\left(1 - \frac{1}{\gamma}\right)}$$

Thus for a logarithmic plot of *dL/dV* versus *L* the slope of the line through all the points is $1 - 1/\gamma$ and so $\gamma = 1/(1 - \text{slope})$. If l_o is non–zero, resulting from non–zero black level or stray light, then there will also be data curvature about the γ line. Again, computer optimisation can be used to estimate a value for l_o such that the data points have no curvature.

The above procedures will have yielded values for l_o and v_o and two values of γ which may not be quite identical due to the effects of measurement noise. The values of l_o and v_o should be used to correct the original measured data values and a conventional logarithmic plot of *L* versus *V* drawn. The slope of the line through all the data points yields a third value for γ. The true value for γ can then be taken as the mean of the three calculated values.

The results should be presented as shown in *Chapter 6*.

5.4. Transfer characteristic – flicker photometry test signal

The subjective assessment yields an indication of γ based only on three data points, black, mid–grey, and white. Measurement is simplified if a test signal is used comprising several patches with mid–grey processed at different values of γ. The method depends on accurate setting of the display black–level, since there is no compensation for the presence of offsets. The recommended test signal [4] includes calibration patches, one at peak white for setting peak luminance level, and two further patches at +2% and –2% for setting black level.

Calculated voltage levels, relative to a peak white of 700mV, for a range of mid–grey signals corresponding to various values of γ are given in *Table 1*.

Table 1 – Voltage levels of mid–grey signals for various values of gamma.

γ	Mid–grey level (mV)	γ	Mid–grey level (mV)
2.0	495.0	2.6	536.2
2.1	503.2	2.7	541.5
2.2	510.8	2.8	546.5
2.3	517.9	2.9	551.2
2.4	524.4	3.0	555.6
2.5	530.5		

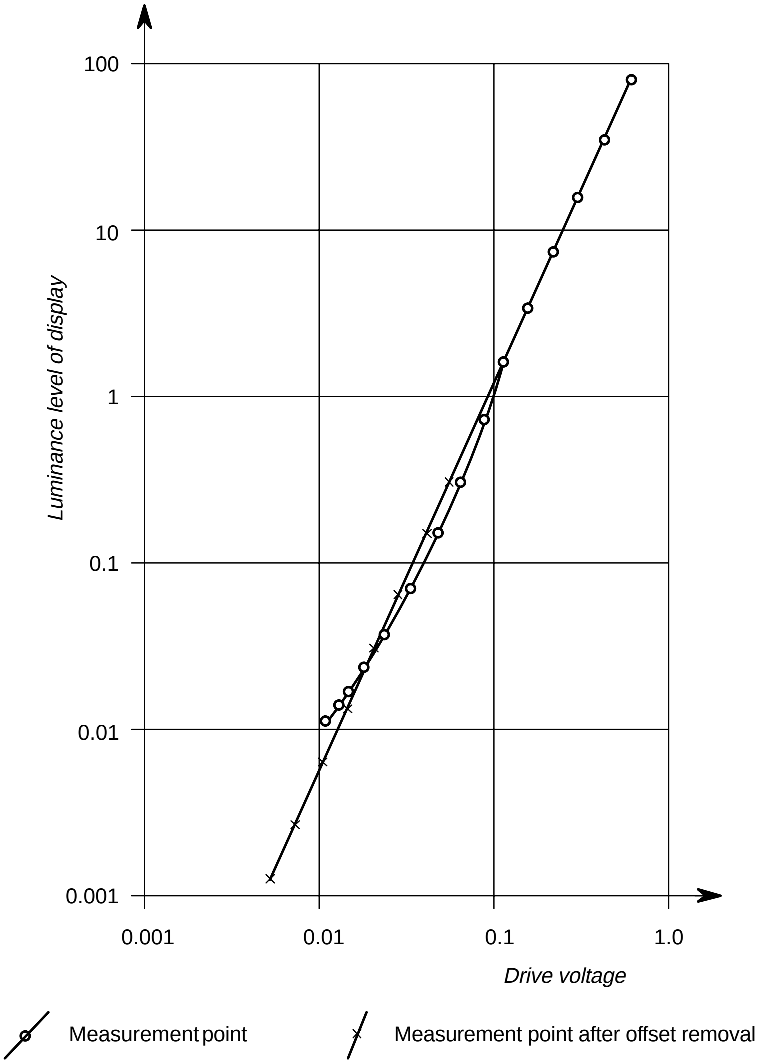
Chapter 6

Presentation of results

The measured and calculated results should be clearly presented. The following pages show the methods and examples of presentation. A summary should be given as shown in *Fig. 7*:

Monitor type:		
Tube type:		
Chromaticities:	**u'**	**v'**
White		
Red		
Green		
Blue		
Gamma (γ)		
Contrast ratio		
Additional comments:		

Fig. 7 – Results summary.



γ from I_o optimisation	2.30
γ from v_o optimisation	2.31
γ from corrected data	2.30
mean value for γ	2.303

Fig. 8 – Typical gamma results (analytical method only).

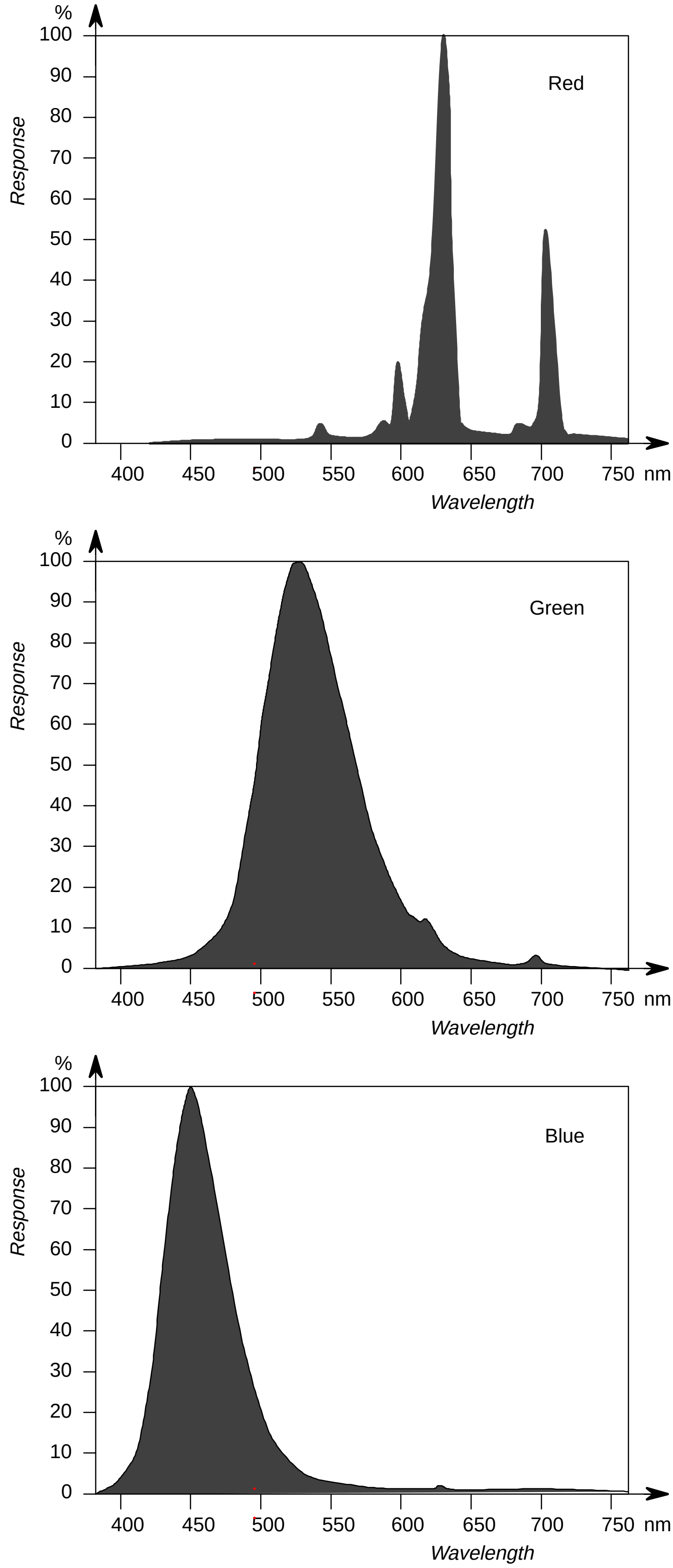


Fig. 9 – Typical spectral radiance characteristics.

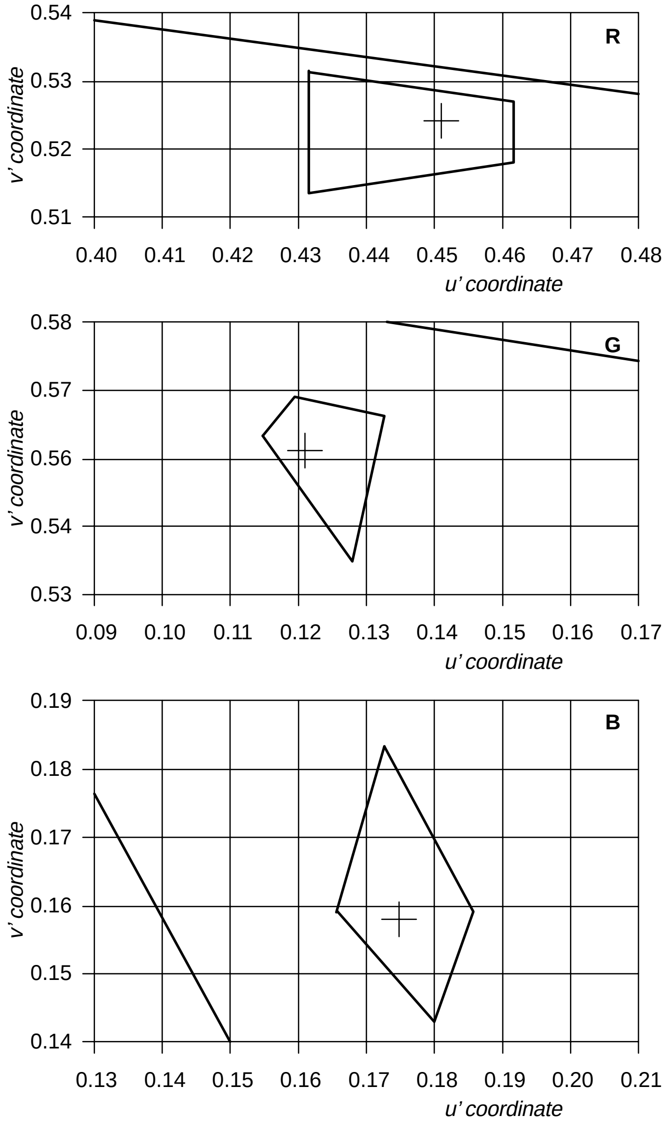


Fig. 10 – Tolerance areas for primary chromaticity plots.

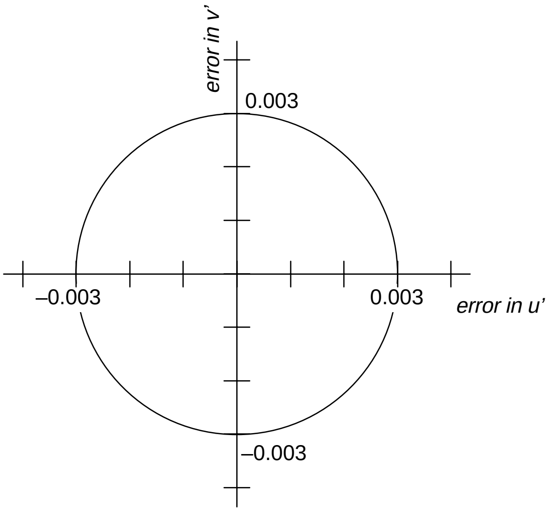


Fig. 11 – Error diagram for the skin tone test colour.

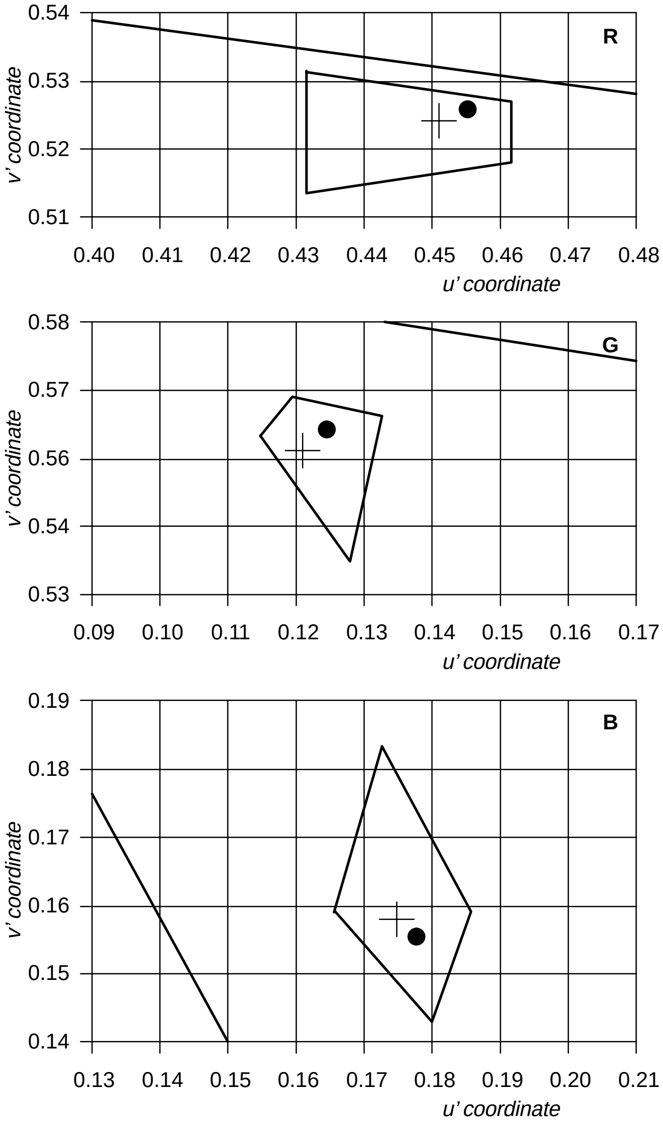


Fig. 12 – Typical primary chromaticity plots.

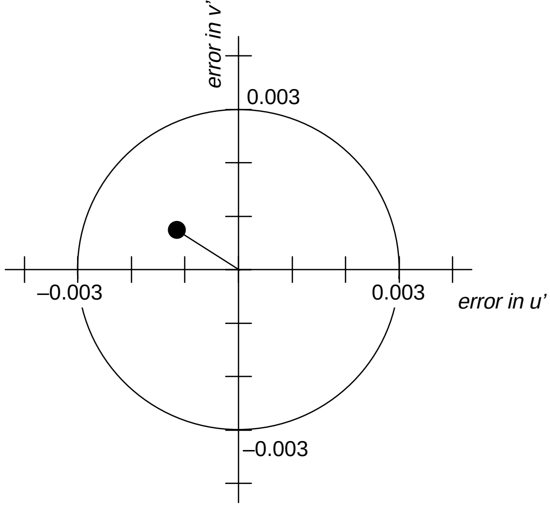


Fig. 13 – Typical skin tone error plot.

Monitor:			**Serial no.:**		**u' v' coordinates for D_{65} (0.1978, 0.4683)**			
Tube:			**Serial no.:**					
	Measured values			**Calculated data**				
Point	**Y(rel)**	**u'**	**v'**	**L***	**Δ L***	**C***	**Δ C***	**Δ E***
1								
2								
3								
4								
5								
6								
7								
8								
9								
(2–5) worst								
(2–9) worst								
(2–5) mean								
(2–9) mean								

Fig. 14 – Results table for white uniformity.

Monitor:			**Serial no.:**		**u' v' coordinates for D_{65} (0.1978, 0.4683)**			
Tube:			**Serial no.:**					
	Measured values			**Calculated data**				
Point	**Y(rel)**	**u'**	**v'**	**L***	**Δ L***	**C***	**Δ C***	**Δ E***
1	1.00	0.1982	0.4681	100.0	–	0.6	–	–
2	0.88	0.1985	0.4698	95.1	−4.9	2.0	−1.4	5.3
3	0.89	0.1984	0.4657	95.8	−4.2	3.4	−2.8	5.3
4	0.89	0.1971	0.4725	95.6	−4.4	5.3	−4.7	7.1
5	0.89	0.1973	0.4672	95.8	−4.2	1.5	−0.9	4.5
6	0.77	0.2014	0.4695	90.4	−9.6	4.5	−3.8	10.4
7	0.74	0.1966	0.4661	89.1	−10.9	3.0	−2.3	11.3
8	0.84	0.1967	0.4685	93.3	−6.7	1.4	.07	7.0
9	0.77	0.1999	0.4711	90.5	−9.5	4.1	−3.5	10.3
(2–5) worst	12%	–	–	95.1	−4.9	5.3	−4.7	7.1
(2–9) worst	26%	–	–	89.1	−10.9	5.3	−4.7	11.3
(2–5) mean	11%			95.6	−4.4	3.05	−2.1	5.55
(2–9) mean	17%			93.2	−6.8	3.15	−2.5	7.65

Fig. 15 – Typical results for white uniformity.

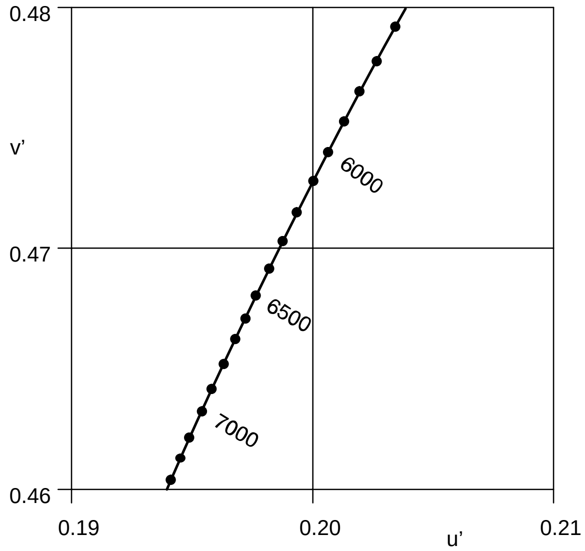


Fig. 16 – Results sheet for white uniformity.

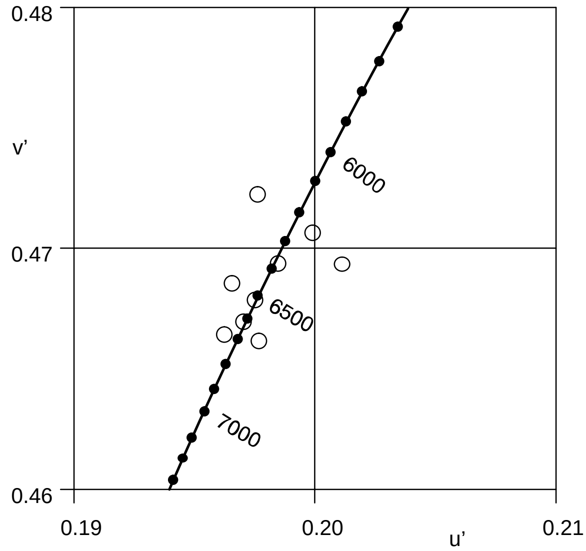
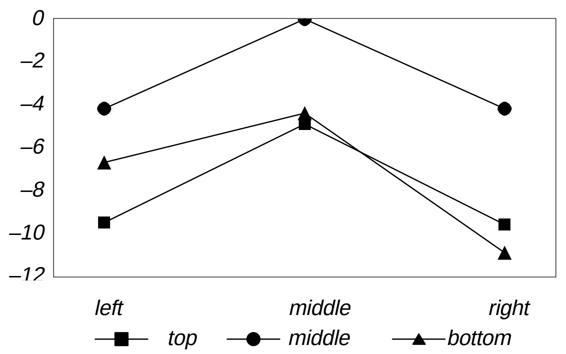


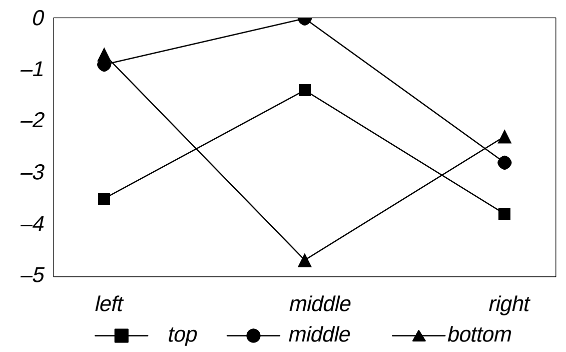
Fig. 17 – Typical results for white uniformity.

	left	*middle*	*right*
top	*–9.5 (–3.5)*	*–4.9 (–1.4)*	*–9.6 (–3.8)*
middle	*–4.2 (–0.9)*	*0.0 (0.0)*	*–4.2 (–2.8)*
bottom	*–6.7 (–0.7)*	*–4.4 (–4.7)*	*–10.9 (–2.3)*

a) CIELuv errors: ΔL*, ΔC*



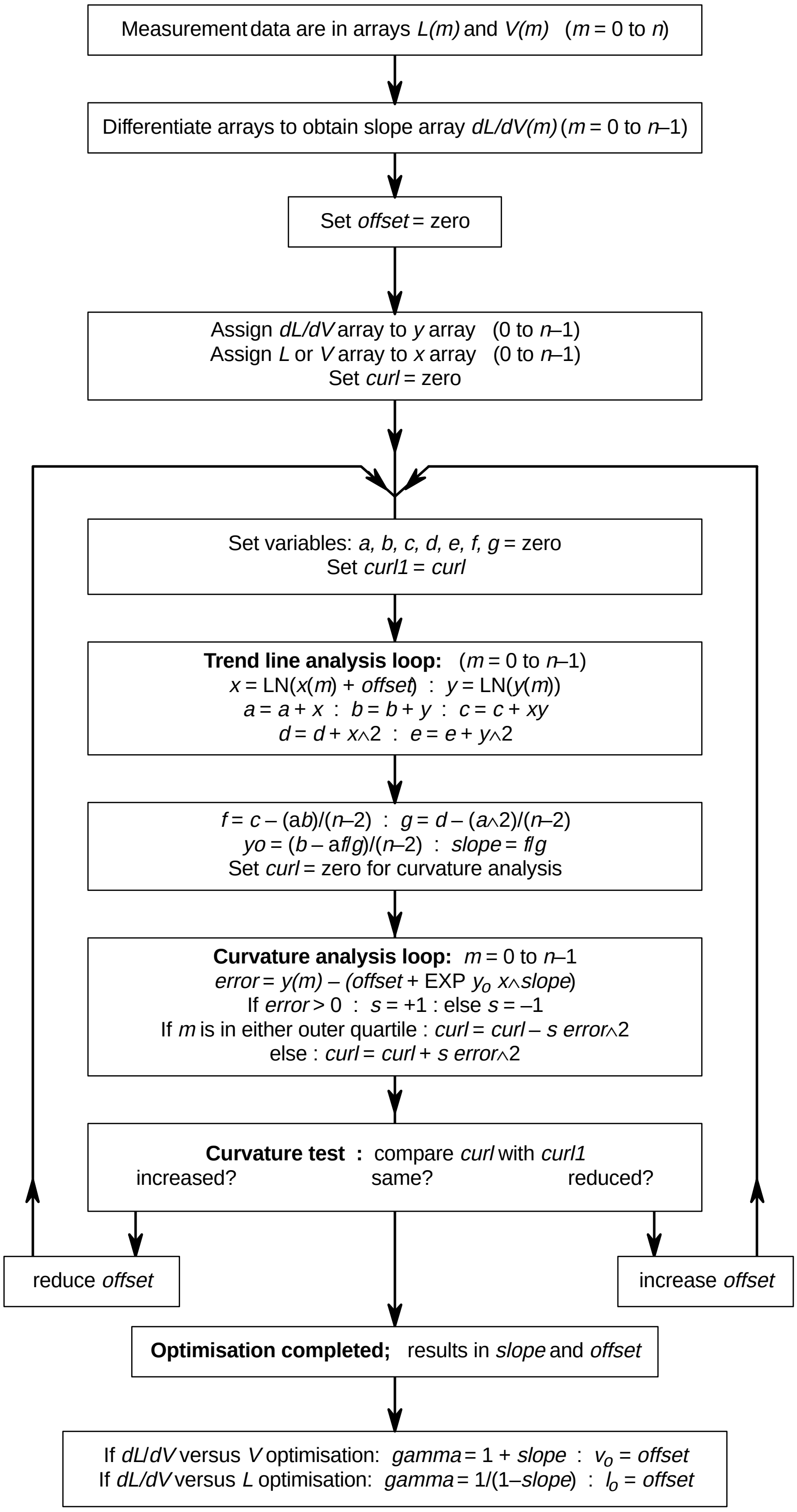
b) Lightness difference, ΔL*



c) Chroma difference, ΔC*

Fig. 18 – Optional additional information for white uniformity.

Appendix 1
Flow diagram of computer algorithm for determining gamma from measured data



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