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NUMBER 65: **DECEMBER 1966**

## Tristimulus spot colorimeter

by

**H. A. S. PHILIPPART, A.M.I.E.R.E.**
**(Research Department, BBC Engineering Division)**



BRITISH BROADCASTING CORPORATION

PRICE FIVE SHILLINGS

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# TRISTIMULUS SPOT COLORIMETER

## SUMMARY

The report describes a photoelectric tristimulus spot colorimeter which measures the three stimuli X, Y, Z, as specified by the C.I.E. (Commission Internationale de l'Eclairage) standard observer, and thus permits simple calculation of the x and y trichromatic coefficients (chromaticity co-ordinates).

In addition to the usual measurements of the colours of materials, the instrument permits measurements of the colours displayed on cathode-ray tube monitors; no such instrument is commercially available. The sensitivity of the instrument is sufficient to permit the measurement of colour at the low luminance levels often encountered in colour television pictures. Further, the narrow acceptance angle of the optical system enables the colour of small areas to be measured at convenient distances from the object.

The dimensions of the instrument are such that, with a power supply unit and meter, the whole instrument is contained in a portable case 41 cm × 36 cm × 15 cm (16 in. × 14 in. × 6 in.).

## 1. Introduction

Assessment of the fidelity of colour reproduction in television usually consists of a number of subjective judgements carried out by the unaided eye. As such, it is subject to wide errors, being dependent on the observer's previous experience, the chromatic composition of the image or scene, the effects of simultaneous contrast, etc. These effects may be known to the observer; nevertheless his judgement may well be impaired.

One of the most sensitive and most accurate methods of assessment of colour is the 'side by side' or matching method using the unaided eye. Whereas this is easily carried out when comparing samples of material, it cannot be used safely with composite pictures; further, it does not give quantitative information, unless comparison samples such as Munsell chips are calibrated beforehand by spectrophotometric means. Colour-picture assessments by the comparison method have often been carried out using duplicate colour slides, one being televised and displayed on a monitor while the duplicate is projected by optical means using a light source whose colour temperature is equal to that of the monitor white. This method has two main drawbacks. First, it is not always easy to obtain exactly identical slides and, secondly, no quantitative colour values are obtained.

Attempts to compare a studio scene with its reproduction displayed on a colour television monitor are subject to gross inaccuracies, as the eye cannot adapt itself easily to allow for changes in chromaticity due to different illuminants and for different levels of illumination.

In order to study the characteristics of a complex colour television chain it is essential that quantitative measurements be made in order to assess the magnitude and location of colour errors in the final picture. The tristimulus spot colorimeter described in this monograph has been developed to fulfil a definite requirement not satisfied by other measuring instruments[1,2] which are, in general, unsuitable for making objective colour measurements on pictures displayed on a shadow-mask cathode-ray tube.

Human vision may be considered trichromatic at light levels in excess of (say) 3 cd/m² (0·9 ft-L) and the standard observer can be defined by three spectral characteristics, $\bar{x}$, $\bar{y}$, and $\bar{z}$ as stipulated by the International Commission on Illumination (or C.I.E.).[3] These curves are shown in Fig. 1 and show the relative amounts of light from each of the three unrealizable primary sources which, when mixed, will produce light of a colour that matches the pure spectrum colour of wavelength noted on the abscissa. The three amounts of light are the 'tristimulus values', noted as X, Y, and Z.

In order to define the chromaticity of a light, only the relative values of X, Y, and Z are necessary. Chromaticity is usually expressed in terms of trichromatic coefficients x and y, which are defined as:

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

The tristimulus colorimeter is therefore required to measure the three stimuli X, Y, and Z.[2,3]

In order to reproduce the characteristics shown in Fig. 1 three methods could be used:

(*a*) A dispersing system with three templates[2] to select correct proportions of the light at each wavelength.

(*b*) Three photocells of known spectral response each fitted with suitable filters.

(*c*) Three colour filters in conjunction with a single photocell of known spectral response.

Method (*a*) results in a very bulky and complex instrument requiring extremely high mechanical stability and very accurate shaping of the three templates, but it does offer the possibility of almost exactly achieving the necessary response. Method (*b*) is also fairly bulky and requires high electrical stability as three photocells are employed. Method (*c*) is the most suitable in terms of simplicity and reliability, even though it does not easily achieve the accuracy of Method (*a*); it can also be adapted to the specified requirements of portability and sensitivity.

There are, however, two major difficulties to the achievement of the ideal tristimulus colorimeter of this type. The first may be appreciated by reference to Fig. 1 where the spectral characteristic of $\bar{x}$ is seen to consist of two pass-

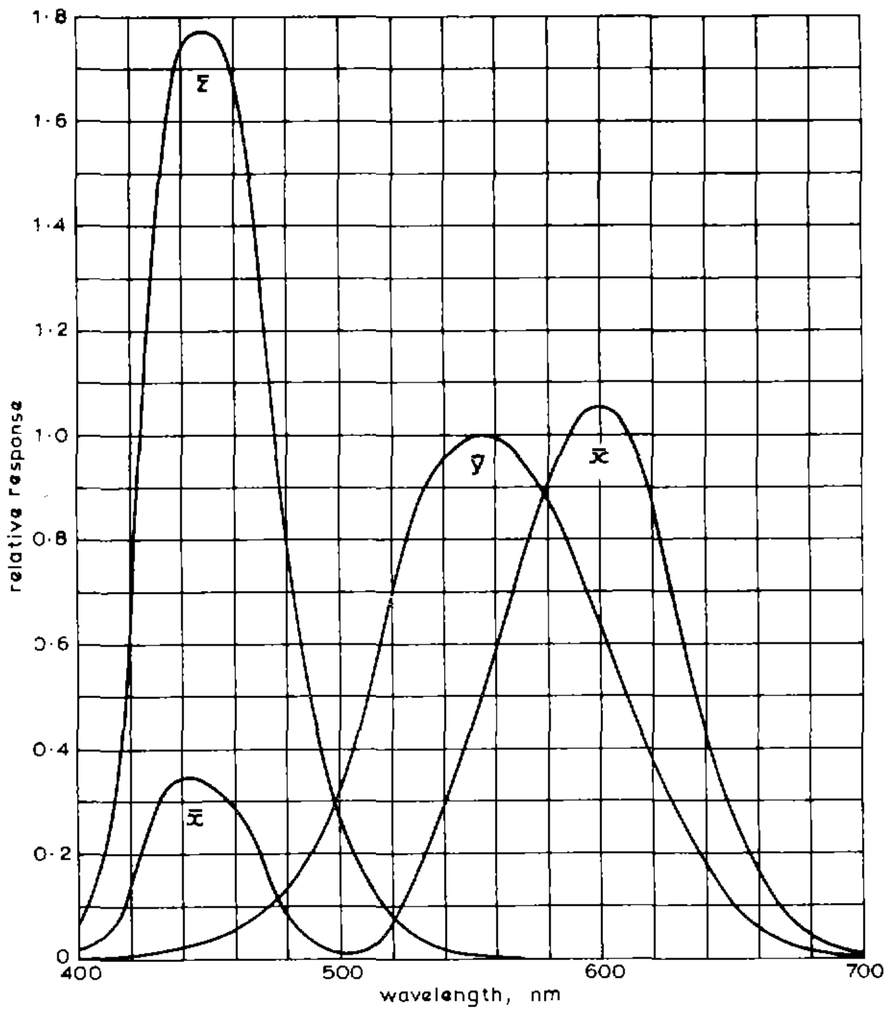


*Fig. 1 — Characteristics of C.I.E. standard observer*

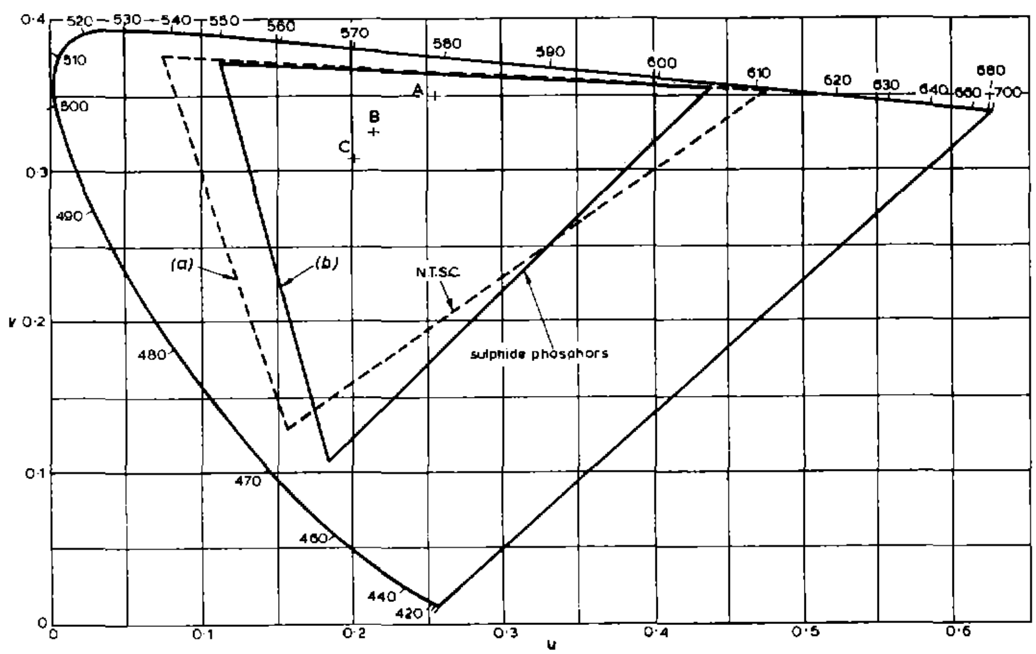


*Fig. 2 — Colour gamuts of a display used*

(*a*) the NTSC phosphors
(*b*) the sulphide group of phosphors

bands which would require a compound filter whose characteristic consisted of a combination of two different spectral characteristics with the appropriate relative areas; this results in a complex filter assembly unsuitable for an instrument of the type envisaged. To overcome this difficulty $\bar{x}$ is synthesized by two separate filters and the two experimental readings are added.

The second difficulty is that due to the limited range of filter material available, whether it be made from gelatine, celluloid, glass, or be of the multi-layer dielectric type. This difficulty may be overcome by stacking several filters of different characteristics so as to obtain the required characteristic, but this, in turn, results in heavy absorption which, added to the fact that measurements of small areas are required, makes it essential that a multiplier photocell be used. The E.M.I.9524F photomultiplier tube has the required sensitivity, spectral response and consistency of characteristic (between specimens of nominally the same tube).

The above considerations show that the whole approach to the synthesis of $\bar{x}$, $\bar{y}$, and $\bar{z}$ characteristics can only be an approximation; nevertheless good accuracy can be achieved over a gamut large enough to cover all types of colour reproduction work, including colour television, which has the largest gamut (Fig. 2).* A useful accuracy is also obtained for absolute measurements over the whole C.I.E. locus. When used for comparison of colours which have similar chromaticities the accuracy is easily sufficient for most practical purposes. In fact, only for the most exacting work should it be necessary to use a reference

* The chromaticity diagram used here is a modification of the original 'xy' diagram proposed in 1931; it has the advantage of being an approximately uniform-chromaticity diagram, i.e. equal distances represent approximately equal perceptible chromaticity differences (at constant luminance).

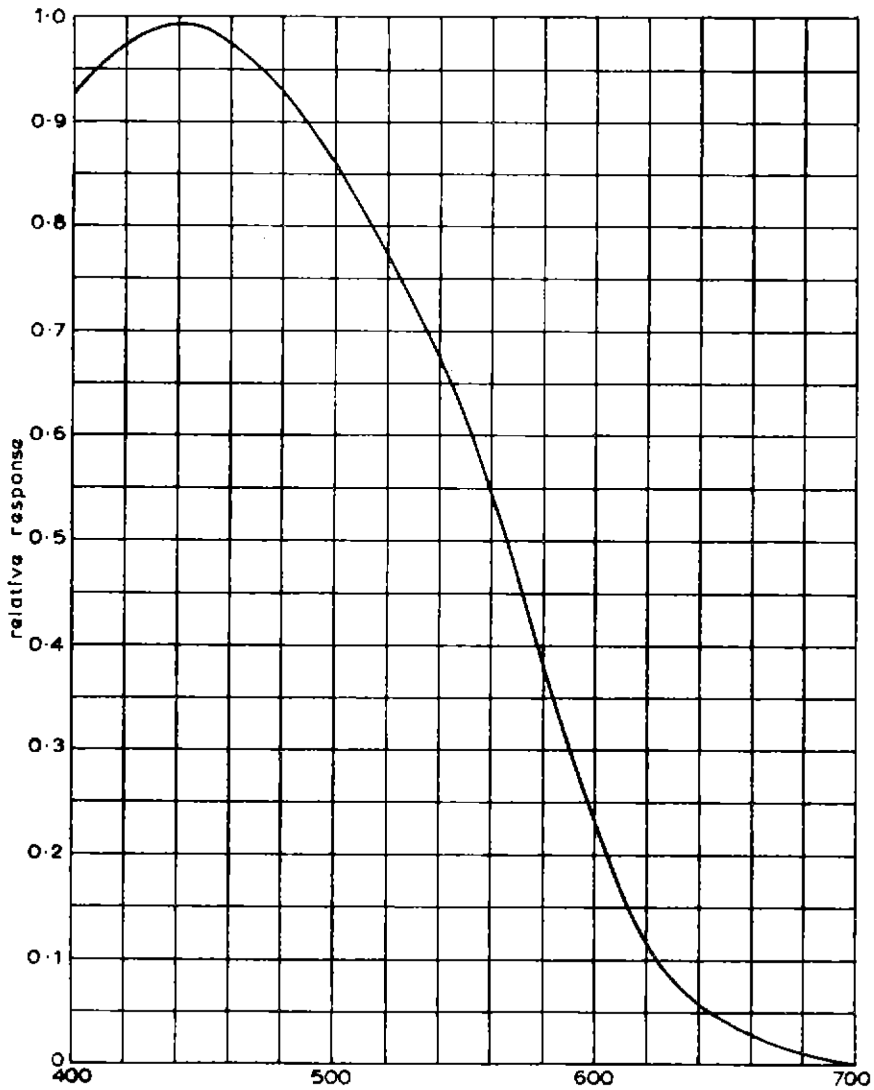


*Fig. 3 — Measured response characteristic of photomultiplier tube as a function of wavelength*

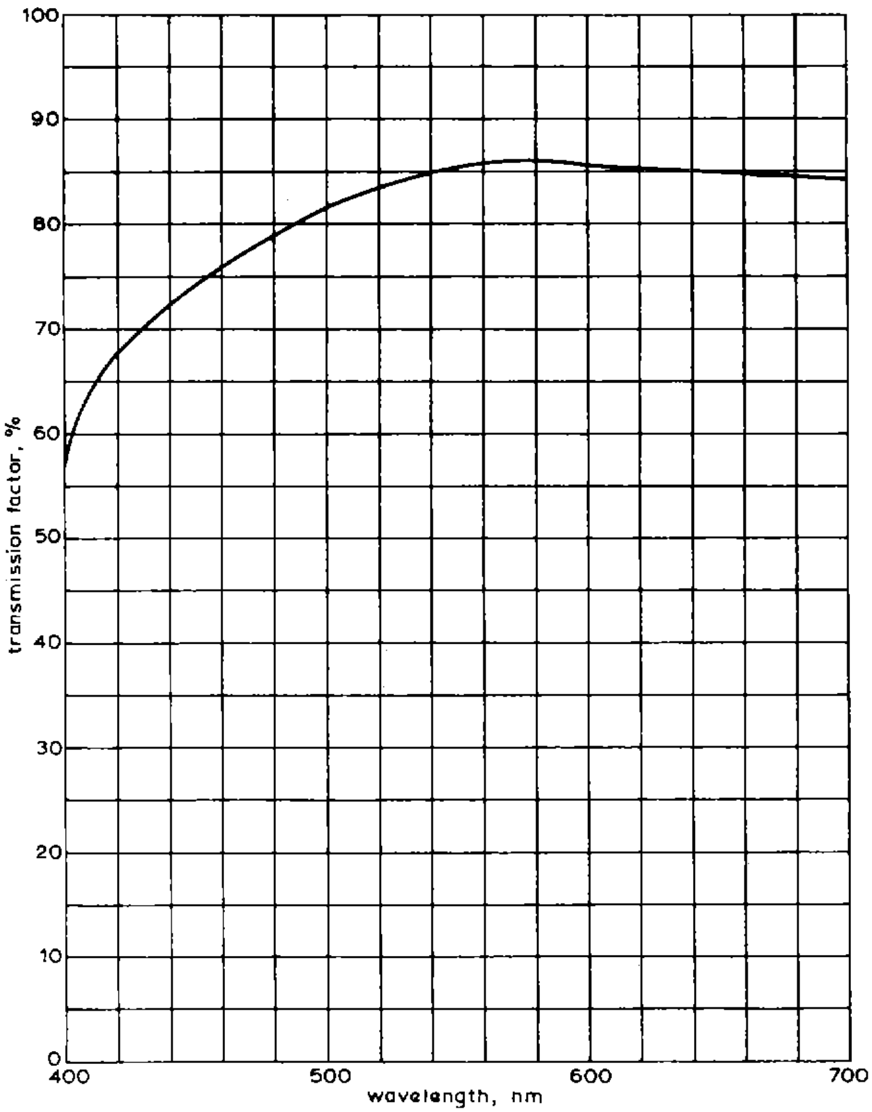


*Fig. 4 — Transmission characteristic of lens as a function of wavelength*

standard. In an instrument of this type, the spectral response of optical components in the path between object and photocell must be taken into account (Figs 3, 4, and 5). Even neutral filters used for balancing the relative amplitudes of the different stimuli must be used with care, as in fact they are only approximately neutral over the visible range, as shown by Figs 6 and 7. Gelatine 'neutral' filters are so unsatisfactory in the extreme blue region that they cannot be used for adjusting the light input to the $\bar{z}$ path. In practice the light inputs to the $\bar{x}$ and $\bar{y}$ paths are adjusted with reference to that of the $\bar{z}$ path, which contains no neutral filter.

Briefly, the essential requirements are as follows:[3]

(*a*) Accurate linearity of response (output versus incident light flux).

(*b*) Zero fatigue and temperature coefficient of the photocell.

(*c*) The combined spectral responses of the colour filters, photocell, and optical components shall be C.I.E. $\bar{x}$, $\bar{y}$ and $\bar{z}$ functions (or linear transformations thereof).

(*d*) The instrument shall have adequate sensitivity for direct measurements of a colour-television picture (i.e. where the peak luminance is approximately 50 cd/m$^2$ (15 ft-L) and the luminance of saturated colours is much lower).

## 2. Description

The instrument is illustrated in Fig. 8 and consists of an objective lens $L_1$ of 75 mm (3 in.) focal length, which images the object to be measured on a ground-glass screen G, the light rays passing through the semi-reflecting mirror M. The image can then be observed by means of

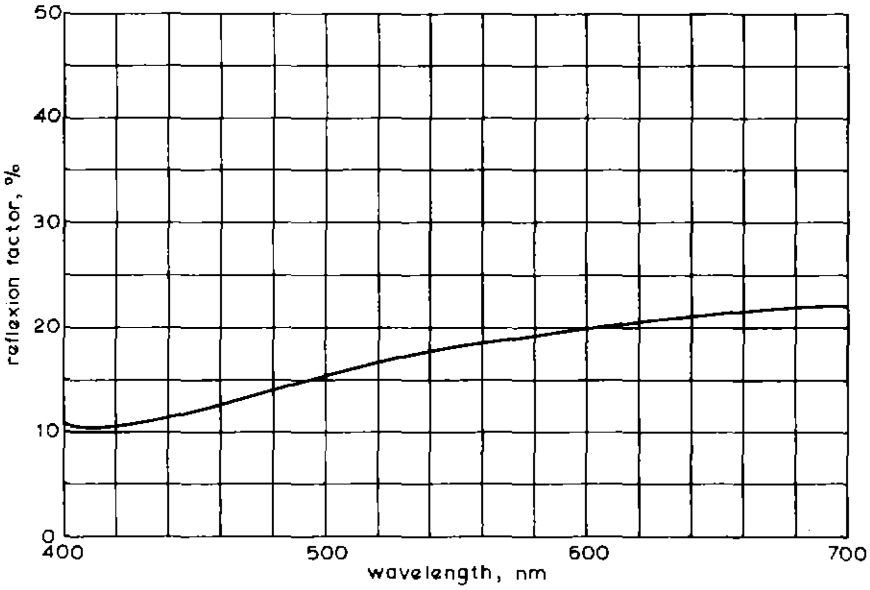


*Fig. 5 — Reflexion factor of semi-transparent mirror as a function of wavelength*

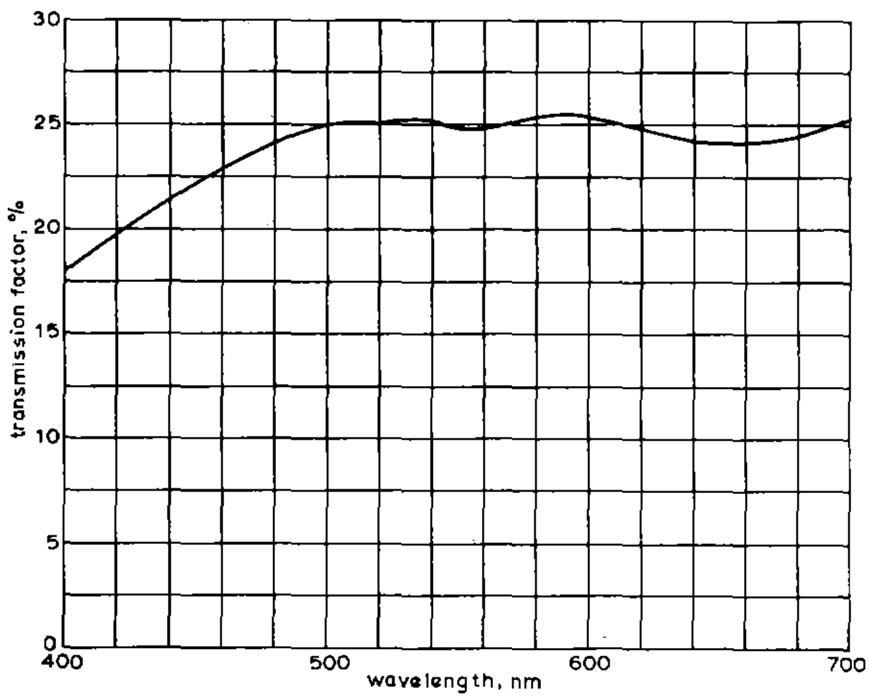


*Fig. 6 — Transmission characteristic of typical gelatine neutral density filter ($ND = 0{\cdot}6$) as a function of wavelength*

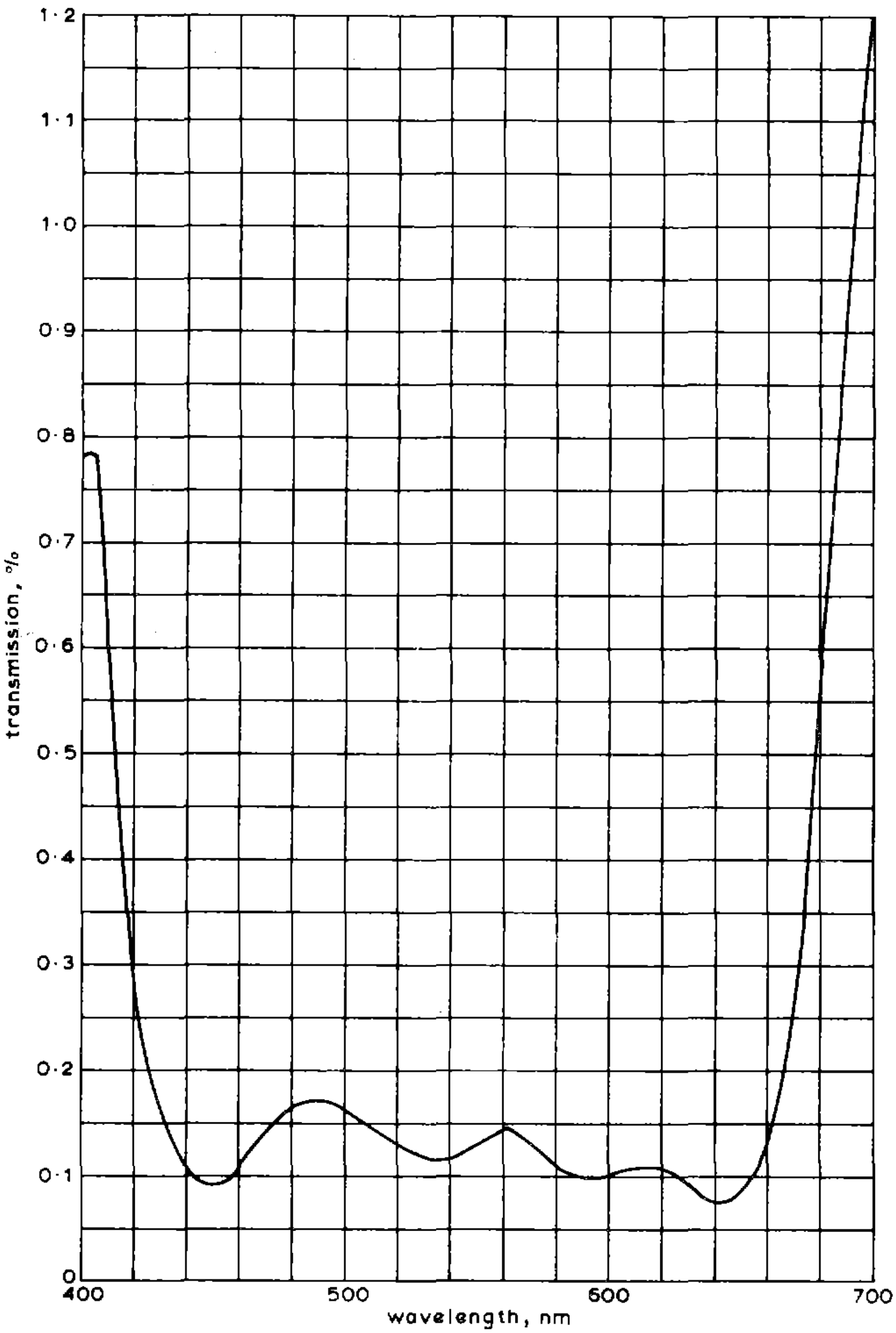


*Fig. 7 — Transmission characteristic of typical glass neutral density filter (ND = 3·0) as a function of wavelength*

the ocular $L_2$. In the centre of the ground glass a black spot T indicates that part of the object which is being measured. The size of the spot, defining the area being measured, corresponds to a viewing angle of approximately 2° or an area of approximately 25 mm × 25 mm (1 in. × 1 in.) at a distance of 0·6 m (2 ft). A Fresnel screen is fitted on top of the ground glass to improve the brightness distribution of the image. A shutter $S_1$ is provided in front of the ocular to prevent light entering the instrument through the ocular when it is not in use.

For measurement, the semi-reflecting mirror M, set at 45° between the lens and the ground-glass screen, deflects a fixed proportion of the light flux into an aperture A situated at a distance equal to the lens-to-screen distance. The aperture corresponds in size to the black disc on the ground glass, thus ensuring that the correct area of the object is being measured.

A filter wheel $F_1$, containing six filters, is located under the aperture plate and is followed by a shutter $S_2$, a fixed filter holder $F_2$, and a diffusing glass D. Lastly there are the multiplier photocell and its associated voltage divider and output potentiometer.

Adjustment of the amount of light reaching the photomultiplier tube is most effectively carried out by means of the lens iris shown in Figs 8 and 9. As already indicated, neutral-filter materials are not truly neutral over the visual range and their use would introduce errors.

Normally in laboratory work a stabilized mains e.h.t. supply is used to power the photomultiplier and the output current is read on a sensitive galvanometer. For other

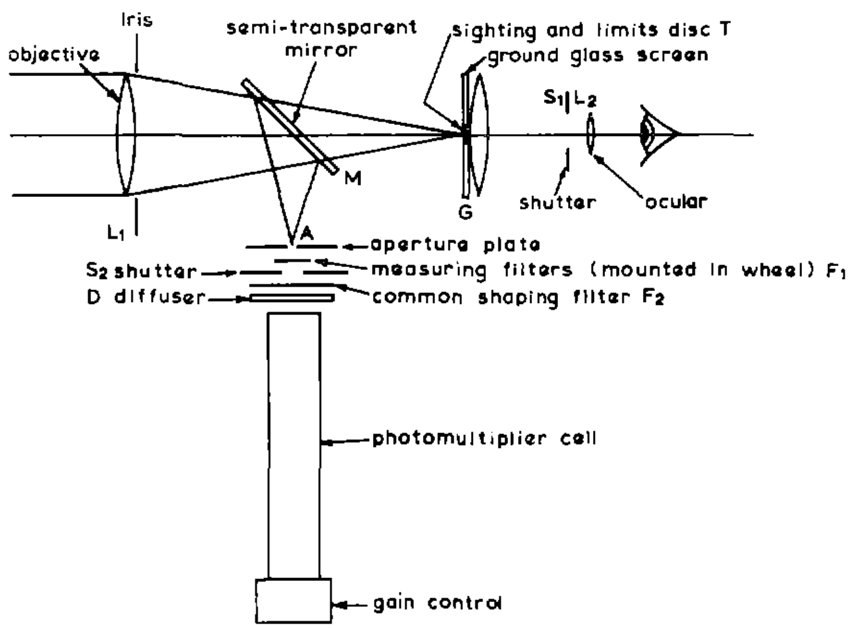


*Fig. 8 — Approximate layout of elements in the photoelectric tristimulus colorimeter*

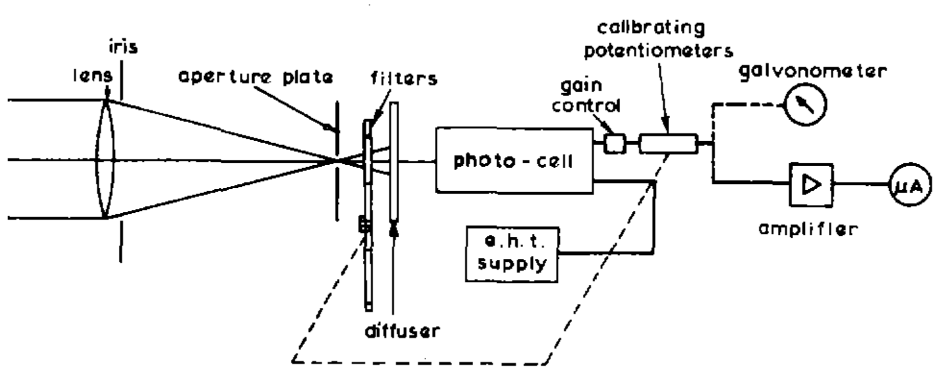


*Fig. 9 — Schematic of the photoelectric tristimulus colorimeter*

applications where portability is essential, a d.c. to d.c. converter, fed from four 1·3V Mallory mercury cells, is used to provide the 1 kV required by the photomultiplier tube. The output of the photomultiplier is applied to a simple transistor d.c. amplifier and measured by a large scale microammeter; galvanometers are usually bulky and insufficiently rugged to withstand transport. Fig. 10 shows a photograph of the instrument and Fig. 11 shows the e.h.t. and meter units in the carrying-case with the colorimeter.

## 3. Analysing Filters

As stated previously, the choice of analysing filters is restricted by the availability of standard filter materials. Therefore filters were selected for the best fit, taking into account the spectral characteristic of the lens, semi-transparent mirror, and photocell. The results achieved are shown in Figs 12, 13, and 14. As can be seen, the $\bar{x}$ and $\bar{y}$ responses are too high at the longer wavelengths (red); this is accounted for by the response of the photocell (Fig. 3) and the fact that no filters are commercially available to correct this characteristic. The realized curves shown are for one specific photomultiplier tube and may vary slightly if the tube is changed.

It is possible, however, to overcome this difficulty by the addition of two extra filters to the filter wheel, these being adjusted in response and density, so that readings taken using them, when subtracted from the X and Y readings respectively, permit correct stimuli values to be obtained. These adjustments are made when calibrating the instrument or when changing photocells; variations in the responses of cells of a given type usually occur at the longer wavelengths.

The filter wheel consists therefore of six filters, labelled $X_R$ (for the red pass-band of X), $X_B$ (for the blue pass-band of X), Y, Z, $-X'$, and $-Y'$; the latter filters are used to correct the readings of X and Y as described. As neutral filters cannot easily be selected to the required accuracy, separate potentiometers are inserted into the output circuit of the photomultiplier for each position of the filter wheel; the potentiometers enable adjustments to be made over a range of $\pm 5$ per cent.

## 4. Calibration

The instrument can be calibrated or checked by means of a standard tungsten lamp of known colour temperature and a series of narrow-band colour filters, these having been previously measured using a spectrophotometer and their C.I.E. tristimulus values computed for the illumination used. By means of these filters, the correct values of $X_B$ and $X_R$ can also be ascertained. A similar procedure can be used for $-X'$ and $-Y'$ but in this case it is important that magenta calibrating filters be used as the required characteristic is given by filters of this non-spectral hue with two response peaks lying beyond the upper and lower extremities of the visible spectrum. Greater calibration accuracy can be obtained if a monochromator is used.

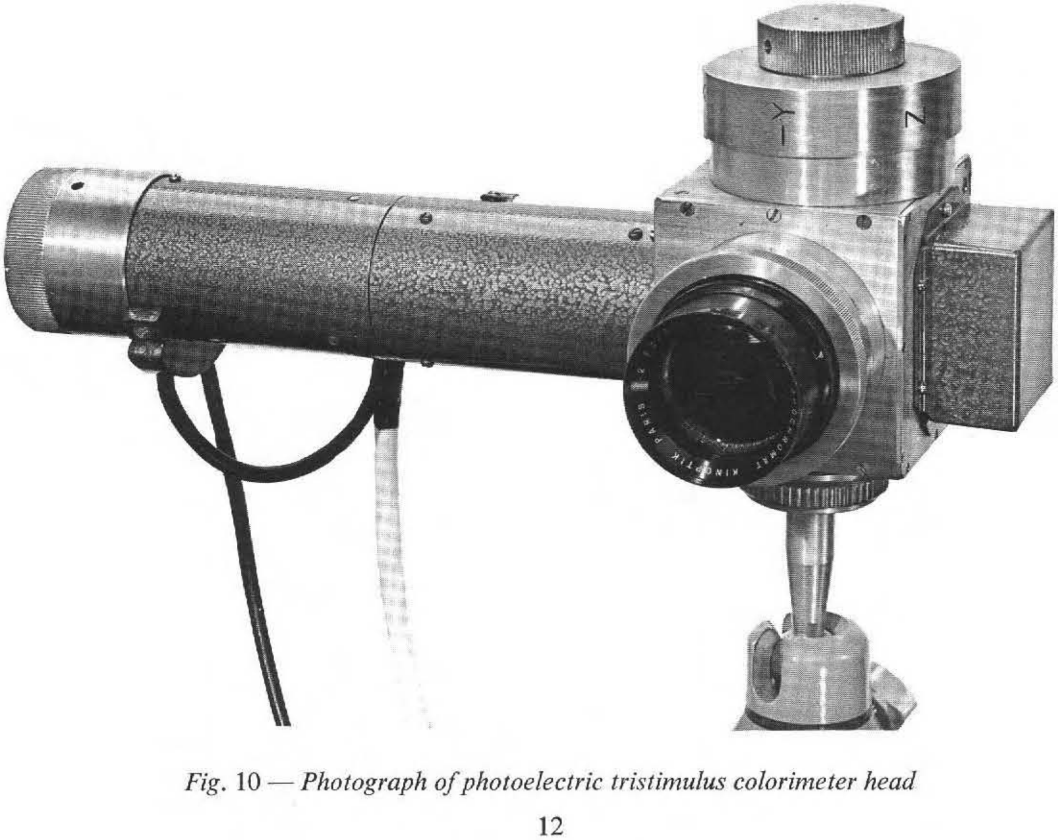


*Fig. 10 — Photograph of photoelectric tristimulus colorimeter head*

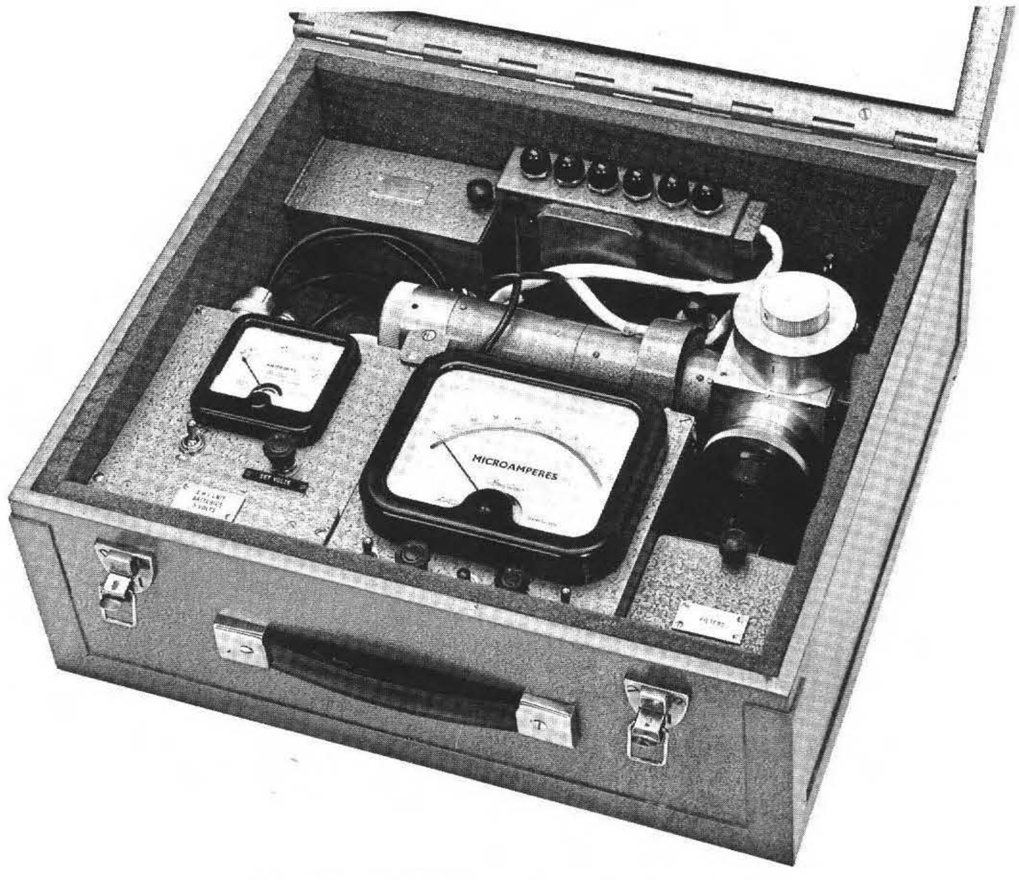


*Fig. 11 — Complete instrument in carrying case*

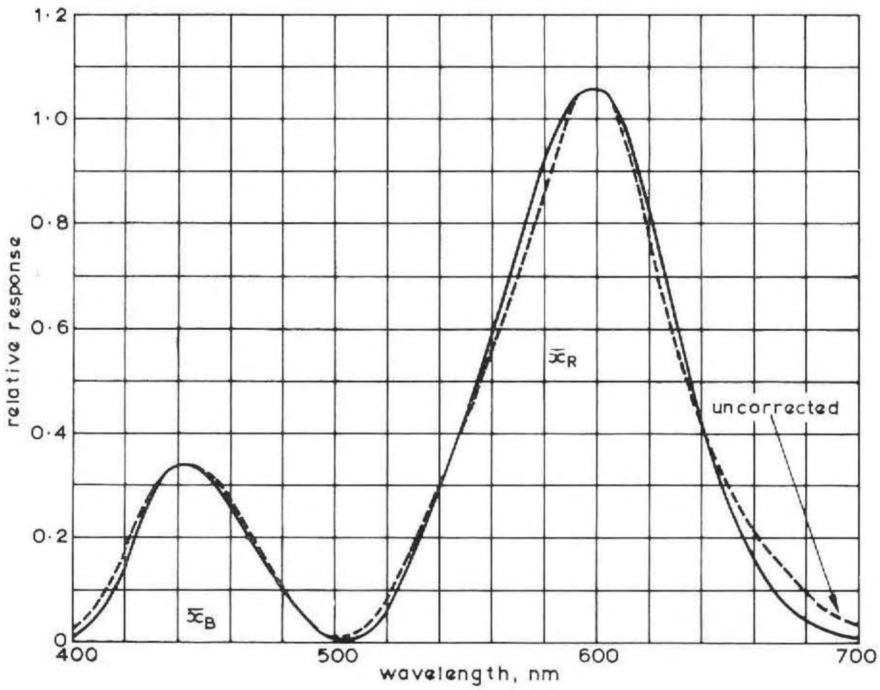


*Fig. 12 — $\bar{x}$ curve and response achieved in the instrument as a function of wavelength*

———— C.I.E. – – – – – – Instrument

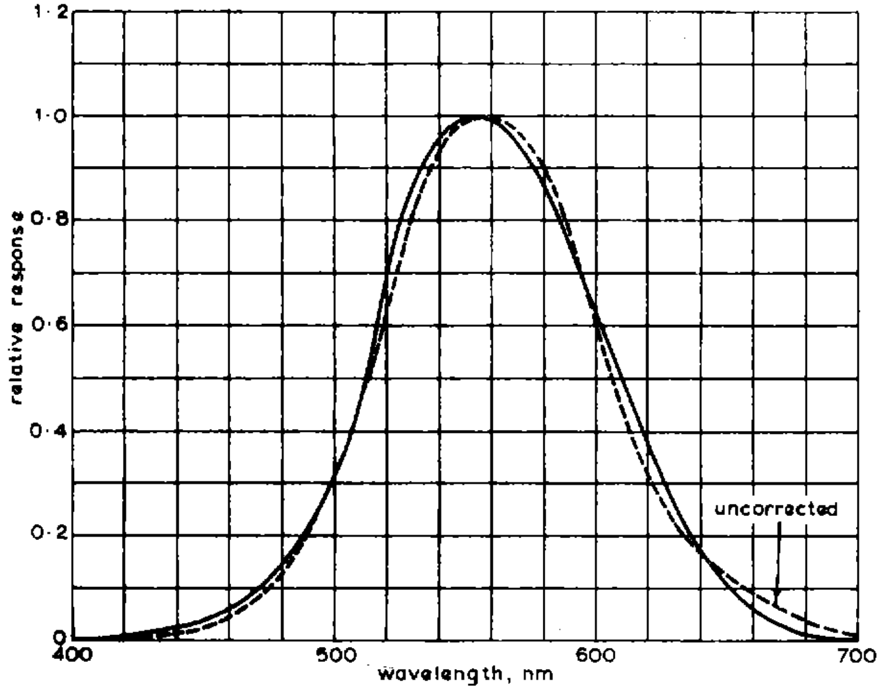


*Fig.* 13 — *ȳ curve and response achieved in the instrument as a function of wavelength*
———— C.I.E. - - - - - - Instrument

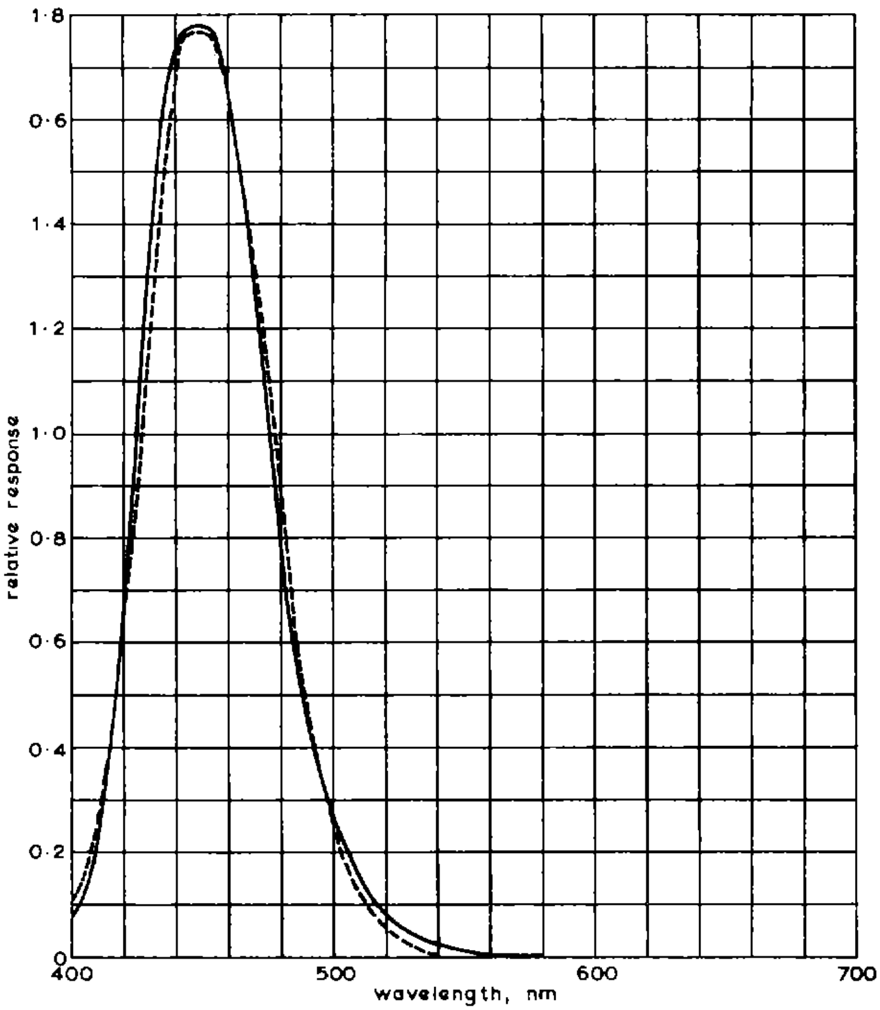


*Fig.* 14 — *z̄ curve and response achieved in the instrument as a function of wavelength*
———— C.I.E. - - - - - - Instrument

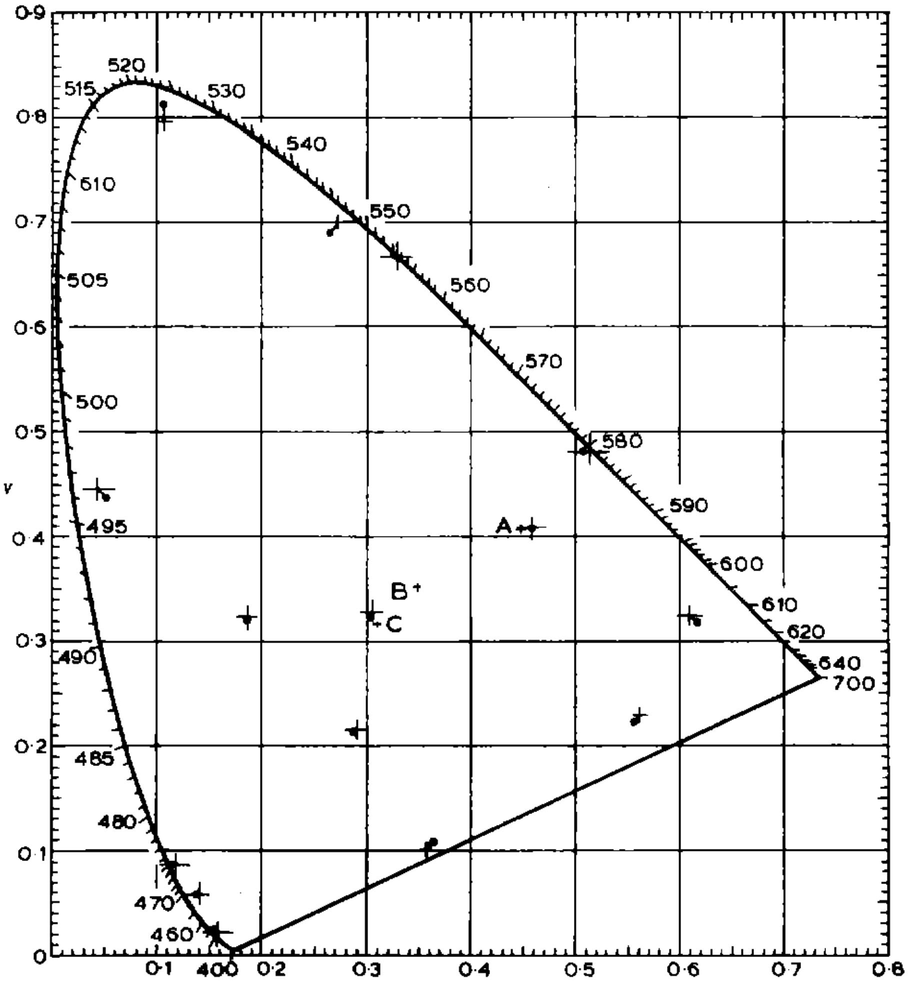


*Fig.* 15 — *Accuracy of the photoelectric tristimulus colorimeter plotted on the* 1931 *C.I.E. chart*

+ Computed ● Measured

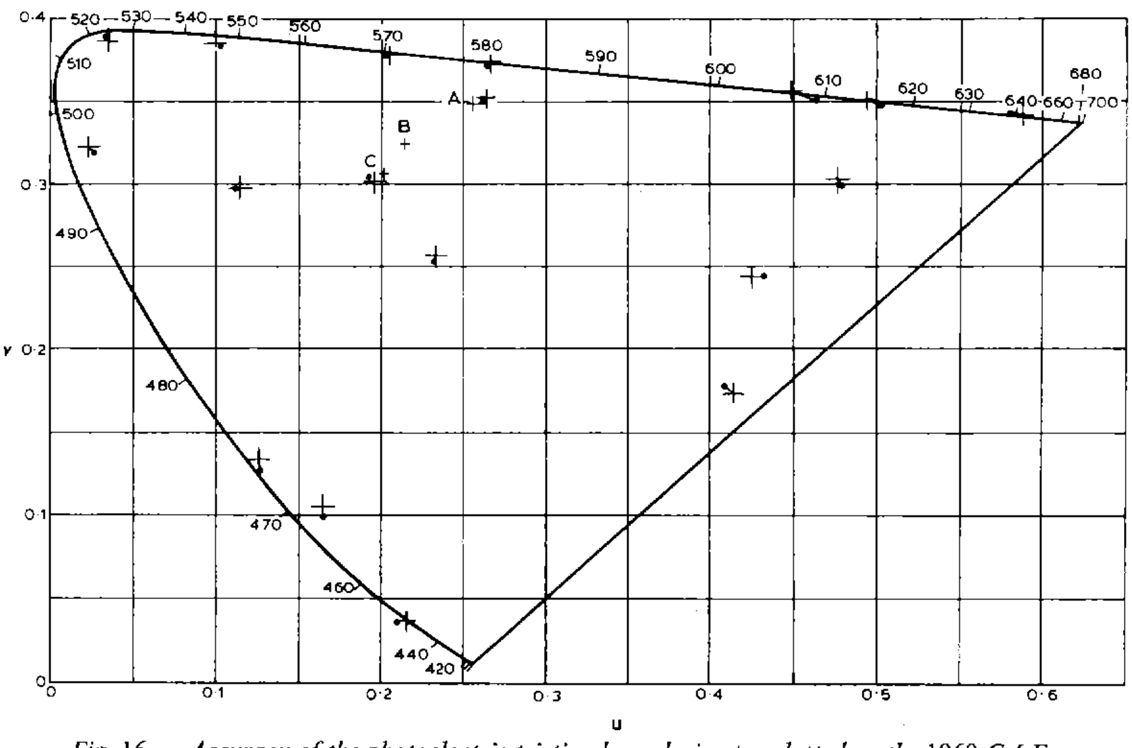


*Fig.* 16 — *Accuracy of the photoelectric tristimulus colorimeter plotted on the* 1960 *C.I.E. 'uniform chromaticity scale' diagram*

+ Computed ● Measured

## 5. Performance

Figs. 15 and 16 show computed and measured values of a series of filters covering a large portion of the C.I.E. colour locus. It can be seen that, as shown on the C.I.E.-U.C.S. diagram of Fig. 16, the greatest error occurs in the red region; nevertheless, most errors are within two just-noticeable differences* (jnds).

## 6. Conclusions

The accuracy of the portable instrument described is extremely good for measurements of small colour shifts and gives sufficient accuracy for most measurements of absolute chromaticity within the colour locus. Nevertheless, improvements may be possible as colour-filter materials and photomultiplier tubes of more suitable spectral response become available.

* 1 jnd is taken as 0·004 units in this paper.

## 7. References

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3. Wright, W. D., **The measurement of colour,** London, Hilger and Watts Ltd, 3rd ed., 1964.

# APPENDIX

## Tristimulus Colorimeter Filters

| | | *Neutral* |
|---|---|---|
| $X_R$ | W81EF, S35, W12, and W12 | Adjusted on test |
| $X_B$ | W81EF and W98 | |
| Y | W81EF, S49, S49, W81EF, and WCC10M | |
| Z | W81EF, S10, and S20 | |
| –X | W81EF, W29, and W34 | |
| –Y | W81EF, W29, and W34 | |

W = Wratten
S = Strand Electric

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CORRECTIONS TO MONOGRAPH NO. 63 (THE DESIGN OF TRANSMISSION LINES AND SINGLE-STAGE SWITCHING CIRCUITS FOR A LINE-STORE STANDARDS CONVERTER).

The following errors have been noted in the above monograph, and copies should be amended as indicated:

Page 8. Right-hand column
In expression (iii), $100F_o$ should read $100C_o$.

Page 12. Fig. 7(*a*)
In right-hand side of diagram ' "write" shift pulse out' should read ' "read" shift pulse out'.
Delay inductors in the ' "write" shift pulse out' and ' "read" shift pulse out' leads should be marked $L_d$.

Page 17. Left-hand column. Clause 7.2.3.1. 2nd paragraph. 5th line.
'A current $i_3$ is induced into the input line' should read
'A current $i_2$ is induced into the output line.'



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