METHODS 0F MEASUREMENT OF THE COLORIMETRIC FIDELITY OF TELEVISION CAMERAS

Tech. 3237 E

May 1983

CONTENTS

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PREAMBLE

After having been among the primary topics for research at the time when colour television systems were being devised, the interest shown by broadcasters in the science of colorimetry has tended to wane in more recent times. This is not to suggest that there have been no practical problems in applying the principles of colorimetry to television, but the difficulties that have arisen have been side-stepped, in a subjectively adequate manner, by ad hoc operational means. Problems elsewhere have been accorded priority, and the users of television apparatus have not examined the question of the colour rendering of their systems with all the scientifically based reasoning that might have been appropriate.

A change was brought about when the EBU began its studies relating to the major items of production equipment. Work started with a view to developing objective methods, which could be reproduced anywhere and at any time, for the evaluation of the fidelity with which equipment reproduces colours. In the meantime, the colorimetrists had not been idle: an objective method had been devised by the CIE for the measurement of light sources, and the principles of this method could be adapted to cover other reproduction techniques. Those who were active in television drew on this research in pursuit of their own studies. An objective method for the measurement of the colour rendering of film scanners was the first target of this work, and now corresponding studies for cameras are under way.

Within the EBU, cameras are studied by Sub group G4 of Working Party G. On the initiative of this Sub group a team of experts has been created to examine the problems of colorimetry and, if possible, to standardise a method for measuring colour rendering. This team, led first by Mr. B. Hisdal and subsequently by Mr. 0. Mikkeli, has not yet completed its work, but it nonetheless seems appropriate to bring together, in a form understandable to the non specialist, a summary of the information that the team has been able to compile so far. This summary is to be found in the present document, drawn up on the basis of a text written by Mr. Hisdal. It is intended to be didactic: it is addressed to engineers seeking to introduce objective colorimetry into their organisations or companies and to those with no particular experience of the methods described here. It is hoped that the publication of this information beyond the team of experts will lead to wider experience being gained with these methods, thus permitting standardisation of the relevant parameters so that the results of measurements may be exchanged meaningfully between users.

To avoid over burdening this document with explanations of the theory of colorimetry, only the essential equations and relationships are given. It is assumed that the reader is familiar with the conversions between values obtained in radiometry (spectral) and in colorimetry (tri variant), with the construction of the CIE M colour space and the EBU RGB colour space, and with the basic principles of colour television.

CHAPTER 1
The need for an objective method

To evaluate how well a television camera reproduces colour, very little use has been made until now of objective methods and in fact no tolerances have been generally recommended. Even now, the colour rendering abilities of a camera are very often described by such terms as "good" or "satisfactory". Such terms are not objective; they express an opinion and this will be influenced to a variable extent by the viewing conditions and by the criteria adopted by the individual observer or group of observers making the evaluation. The use of a subjective judgement for the evaluation and the final adjustment of the colour is, of course, common practice in every day operational procedures. But, beyond that level of operation, there is a need for an objective specification which can be used in acceptance tests, which will have a well defined significance, and which can easily be implemented and generally understood by both broadcaster and manufacturer.

An objective method for specifying camera performance is also desirable for other reasons. One is this: to obtain high quality colour rendering, it is necessary for the spectral response of the camera to approach a given set of characteristics. This requirement is met by inserting combinations of dichroic and absorption filters in the optical path and by equipping the electronic circuits of the camera with matrices taking into account the spectral characteristics of the lens and the camera pick up tubes. However, large amounts of optical filtering and the electronic matrixing operations result in a reduction of the overall sensitivity and of the signal to noise ratio. A certain balance can therefore be established between the colorimetric performance, sensitivity and signal to noise ratio. Until such time as there are objective methods for the evaluation of the colour rendering properties of cameras, it is difficult to quantify the extent to which the 'optimum balance has been achieved.

As the* basis for the objective method, an attempt could be made to describe the colour rendering by considering only the physical quantities relating to measurements taken at the camera output, or other physical quantities that can be derived from such measurements. But this would be to neglect the fact that the purpose of a television system is to produce a picture and that this picture is to be appraised by the human eye. It is therefore necessary, when assessing the effect of the system, to use parameters which take account of the sensory effect of light. The colorimetric quantities meet this requirement. They also meet the requirements for a mathematical treatment of colour analysis: with data obtained from measurements of the perceived spectral colours, it is possible, by means of calculations, to determine the effect of any colour on an average observer. Any colour, given its spectral power distribution, can thus be specified in an objective and universal way.

The colorimetric quantities have been established following very extensive research by the Commission Internationale de l'Eclairage (CIE) and they have come to be used very widely when objective evaluations of colour have to be made in a practical field. The reasons for their almost universal adoption are to be found in the nature of the experiments used to determine them in the first place. These quantities were established on the basis of assessments of visual equivalence. They are therefore especially well suited to the various techniques used to reproduce colour (photography, printing, paints, television) where the primary aim is to adjust certain colours to match other colours, whether they be originals or references, in order that they might produce the same sensation. When this effect has been obtained, the reproduction is considered as faithful.

If we examine the parameters that need to be adjusted in television in order to achieve this fidelity, we find that we cannot impose the reproduction of the real luminance of the points of the scene. In effect, the range of luminance values that can be reproduced on the screen of the receiver is small in comparison to that occurring in nature. Nonetheless, the accommodation of the eye to suit the intensity of the illumination it receives is such as to largely nullify the influence of the real luminance level on the perceived colour sensation. If we wish to quantify the quality of the reproduction, we can therefore accept larger tolerances for the luminance than for the chrominance.

The receiver imposes another constraint. With a given set of phosphors and a given alignment of the grey scale neutrality, the screen can only display, as a colour for an object, the colour which matches the one the object would have had under a particular type of illumination. In television systems conforming to the EBU chromaticity standards, this illumination, which corresponds to the receiver alignment, is that which can be matched by white D_{65}. If some other form of lighting is used during camera operations, the camera circuitry has to perform a process rather similar to the chromatic adaptation of the eye when it moves from one form of illumination to another. Colour correction of this sort may be realised by modifying the channel gains in the camera in order to obtain equality of the tristimulus values for white D_{65}. This corresponds mathematically to a change of unit vector in a Cartesian frame of reference. When it is combined with the matrixing, this processing takes the form of ensuring a correspondence, colour by colour, of the analysis colour space and the display colour space, the primaries and the reference whites for these spaces being different.

Therefore, the picture by which the colour rendering of cameras will be assessed will generally not be that which could be perceived by observing the scene directly. Instead, it will be that which would be displayed to the viewer after transmission and decoding in standardised conditions. The ideal according to which this picture will be judged will be that which would be obtained if the same final conditions were associated to theoretically perfect analysis conditions. Television reproduction will therefore be regarded as faithful when the displayed colours match those of the object when the latter is under lighting having a spectrum the same as that of illuminant D6.. It is in this sense that we should understand the term 11colour fidelity" in the present context.

We will not go into all the details of the formulas serving to determine the various colorimetric parameters because these are explained in the works referred to in the bibliography, all of which are readily obtainable. The basic CIE recommendations are given in document [1], whilst works [2 to 5] explain their applications. In Chapter 6, however, we will set out all the details needed for the calculations to be performed in television.

CHAPTER 2
The CIE system of colour measurement and colour rendering

2.1. Principles of the CIE system of colour measurement

An objective method for the specification of colour must be independent of any variable influences related to the experimenter and the measurement conditions. The only principles which have been presented so far which can serve as the basis for such a method are those defined and recommended by the CIE [1]. In the CIE system, to eliminate the subjective variations in the evaluation of colour by each individual observer, the perceived colour is calculated from objective measurements of certain values that are related only to the physical characteristics of the radiation. This calculation brings into play an imaginary person, the standard colorimetric observer, whose visual characteristics have been defined statistically from experiments conducted within the CIE. The standard observer is deemed to represent the average of all normal observers in certain specified conditions. At the present time, two standard observers have been defined. One is the 1931 2° observer (for visual fields, applied to coloured areas, between 1° and 4°) and the other is the 1964 supplementary observer (the so called 10° observer) for fields of more than 4°. These observers are each defined by a set of three colour matching functions ($\bar{x}_l$, $\bar{y}_l$, $\bar{z}_l$) which give, for the whole visible spectrum, the tristimulus values of the X, Y and Z primaries for a match to monochromatic radiations of equal power.

Colour representation in the XYZ system is only an intermediate step of computation. Other co-ordinate systems are more appropriate in representing the visual effect of colour differences. The results can be presented in a two dimensional colour diagram (without any luminance information), or in a three dimensional colour space. The CIE has defined and recommended two colour diagrams which are approximately uniform. These are the CIE 1960 u, v diagram and a modified and improved version known as the CIE 1976 u', v' diagram. Also, two approximately uniform colour spaces have been defined, these being the CIE 1964 U*V*W* space and an improved version, the CIE 1976 L*u*v* space, commonly referred to simply as CIELUV. The U*V*W* and L*u*v* spaces are not obtained simply by juxtaposing of a chromaticity diagram and a scale of perceived luminance. In developing them, an attempt has been made to take account of an experimental observation that chromaticity differences become increasingly perceptible if the luminance is increased. That is why the perceived "colourfulness" of a colour is obtained by applying a weighting factor to the values of the chromaticity diagram which is proportional to the lightness of that colour. The measurement of colours therefore approaches classification systems in which the colours are arranged in a regular scale of subjective differences.

An L*a*b* space has also been recommended, but it will not be considered further here because it is not suitable for television. These spaces are intended to be approximately uniform in terms of the perceived impression: if they were perfectly uniform, equal distances within the spaces would correspond everywhere to the same difference in perceived colour. The divergences from total uniformity, within small regions of the spaces, are sufficiently small to permit their use in many practical applications.

2.2. Principles of the CIE method for the measurement of colour rendering

A method has been devised by the CIE [7] to measure the colour rendering of light sources and it is not, therefore, directly applicable to the case of television. Nonetheless, the fundamental concepts of the method can be used, as can certain of the parameters determined by calculations.

The CIE method uses a number of samples which are representative of the range of colours encountered in practical situations. The evaluation of the colour rendering is based on the determination, for each of the samples, of the difference between its original colour and the reproduced colour. This difference is measured as the length of the vector which, in the 1964 U*V*W* colour space, joins the points representing these two colours. This parameter is called the colour difference and is designated by the symbol ΔE . Owing to its three dimensional nature, it covers all three attributes of colour and indicates, therefore, the overall effect of a distortion of a given colour. The space in which it is calculated is almost uniform and so we can consider that it gives a suitable means of expressing the fidelity of the reproduction, in the sense given in Chapter 1; the reproduction will be said to be perfect, in colorimetric terms, when the colour difference is zero.

2.3. Adaptation of this method to suit the requirements of television

The methods for television which are based on these principles, make use either of real samples or of theoretical samples. In both cases, these samples are assumed to be diffuse reflectors and non fluorescent. The calculation of their colorimetric parameters is done on the basis of data corresponding to the 1931 (2°) standard observer (this choice is governed by the dimensions of the coloured areas as seen on the receiver screen).

As explained earlier, the calculation will not always be based on the true colours of the samples as, whatever scene illuminant may be used, we will take into consideration only the colours obtained with illuminant D_{65} (the latter, in a way, constitute reference colours). The original reference colours of the samples are calculated from their spectral radiance factors, measured in a specialist laboratory (real samples) or defined (theoretical samples), and from a set of data published by the CIE (spectral energy distribution of Illuminant D_{65} and the colour matching functions ($\bar{x}_l$, $\bar{y}_l$, $\bar{z}_l$).
The reproduced reference colours are determined, for real samples, from the signal levels at the camera output, using a matrix equation to convert the values from the EBU system of RGB primaries to the CIE XYZ system. For theoretical samples, a calculation similar to that for the original colours is used to give the reproduced colours on the basis of the spectral energy distribution of the illuminant, the relative spectral sensitivities of the three channels of the camera and the spectral radiance factors of the samples.

The concept of colour difference is also used in television (it should be pointed out, however, that the term presented.here is used exclusively in calculations relating to television colorimetry; it has nothing to do with the formation of the B Y and R Y signals which, in the television chain, carry the chrominance information and which, unfortunately, are also known as colour differences). In the form in which it was developed by the CIE, the concept of colour difference applies to surface colours examined by an observer which is adapted to a field of chromaticity not too different from that of average daylight [1]. This criterion is in agreement with the reference conditions imposed by the chromaticity standards for television receivers. The colour difference of the samples will thus be determined for illuminant D_{65}, regardless of the spectral distribution of the light actually falling on them. In this document, only the calculation of this parameter in the CIELUV space will be considered; it will be designated by the symbol ΔE^*.

In common with the U*V*W* space, the CIELUV (or L*u*v*) space is based on a colour distribution which approximates to that adopted in the Munsell colour order system. The colour difference calculated in such a space constitutes a sufficiently accurate approximation of the difference effectively perceived between two given stimuli when these are relatively similar - at the threshold of differentiation or very close to this threshold. Of the existing colour spaces, the L*u*v* space Is the best suited to the present application. Compared with the U*V*W* space, from which it derives, it shows a small modification in the measurement of lightness (L* replaces W*) and this modification has repercussions on the colour parameters, which are related to the lightness by unchanged relationships. More importantly, it differs from the U*V*W* space in the use of the u' and v' co-ordinates, which are more "uniform" than u and v, as the basis of the measurement of chromaticity.

The L*u*v* system is not accepted totally without reservation for television. It is adopted here in the absence of any other more acceptable system. However, any future yardstick is likely to be calculable from this data.

The relative spectral energy distribution of illuminant D_{65}, as well as the colour matching functions $\bar{x}_l$, $\bar{y}_l$ and $\bar{z}_l$, are reproduced on pp. 35 36 of this document.

2.4. Choice of representative values

To give an expression of the colour rendering properties of light sources, the CIE recommends the use of colour rendering indices; these are obtained from the colour differences ΔE (in the CIE 1964 space) by means of the following formula:

$$R = 100 - 4.6\Delta E$$

The use of this parameter has also been proposed as a means of specifying the colour rendering of television cameras [8]. We will not pursue this proposal for the following reason.

Perfect reproduction is characterised by an index of 100 (or zero colour difference). As ΔE increases, zero or negative values of index can be obtained. However, the physical interpretation of these values is no different to that of positive values (a value of 0, for example, does not imply the absence of colour). Proposals designed to remedy this difficulty are being investigated by the appropriate Committee of the CIE. If the colour fidelity of the television camera must be evaluated by means of a concept of this sort, it would seem more helpful to use the colour difference itself as this will always be positive. The ΔE unit is similar also to the "overall just noticeable difference" ("overall jnd") which has been defined by the BBC and which combines the effects relating to both the luminance and the chromaticity.

The concept of "jnd" is very frequently used in studies of television colorimetry [9], but this is not defined in the CIE colorimetry system. The colour rendering index gives no information that is not already supplied by ΔE and so there is nothing lost in restricting the studies to this latter value. It will be the only parameter used in the remainder of the document and, as mentioned above, it will be calculated in the CIELUV colour space (symbol $\Delta E*$).

Various statistical values have also been proposed to characterise colour rendering including, in particular, the arithmetic averages of the indices or of the colour differences for a certain number of samples. As can be seen hereafter (see Section 6.6), these parameters may be used to classify cameras according to their colorimetric performance but it is felt that, for acceptance tests, they are not enough, by themselves, to give a precise indication of the individual performance of a camera.

No correspondence will be determined between the calculated objective colour difference and the acceptability of that difference. In effect, acceptability is a subjective concept and it may vary from one person to another and according to the type of colour, the application, or the scene to which it refers. Every day experience shows that, if it is to be acceptable, the reproduction should not necessarily be colorimetrically correct. As a result, the colour difference In the CIE colour measurement system is taken as being representative only of the perceptibility of colour shifts, not of their acceptability.

The divergences that have been mentioned between the colour spaces and uniform perception, and the lack of correspondence between the calculated data and the acceptability of the colour shifts to which they relate, are representative of some of the limitations of the CIE system. A more detailed discussion of this aspect, and of the colorimetric problems it poses, will be found in the works listed in the bibliography. These problems have led to the expression of doubts regarding the usefulness of the CIE system. Nonetheless, the system has been used for a number of years in various practical applications [7 to 9], and that would certainly not have been the case if the method had not been thought valid. It is not really surprising that this is the case as the formulas that have been produced are in no way arbitrary but, instead, they incorporate the results of a large number of investigations into colour vision.

Whatever its shortcomings, the CIE system is the only objective system for colorimetric measurements which has been accepted internationally. It Is to be hoped that it will also prove to be a useful tool for the measurement and evaluation of colour fidelity in television. This hope is based on the experience of television colorimetry available so far, in certain organisations. To quote from one such organisation [9]:

"Despite these limitations, it has been found from past experience that if the optical design and associated matrices are computed for an objective accurate colour reproduction (with idealized linear camera tubes and a linear display), then the camera will have good colorimetry, and only minor matrix adjustment will be needed to achieve a subjectively satisfactory result."

Keeping the advantages and disadvantages of the C IE system in mind, the methods presented here should be considered more in terms of a first attempt at objective camera evaluation than as a final and perfect proposition.

CHAPTER 3
Special conditions to the measurement of cameras

Any method envisaged for the measurement o the colour rendering of cameras must, if it is to be of any practical use, meet certain requirements: accuracy, ease of implementation, speed of manipulation and calculation, reasonable cost of equipment and easy familiarisation by staff, etc. Of course different levels of each of these factors may be aimed at. As we have said in Chapter 1, we are considering acceptance tests here; in such circumstances, ease of implementation and rapidity may take second place behind accuracy, for example. Also, different organisations may wish to be able, on the basis of these measurements, to obtain different sorts of information. Nonetheless, only methods based on a minimum of scientific and mathematical theory can be really effective when it is desired to define a common language for broadcasters and manufacturers.

Several methods have been described to measure the colour fidelity of television cameras. Here we will concentrate mainly on the spectrophotometric method and the real samples method. Both are based on the same fundamental equations and, in principle, they will allow the same degree of precision to be attained in a linear system. They will be described in Chapter 4 and 5. In Appendix 5 there is a brief description of a method using an interference filter and of another using electronically generated test colours.

Other methods may be necessary for operational tests: their objective may be to seek out anomalies in colour rendering which will subsequently be analysed in detail by maintenance staff. This subject will not be covered in the present document.

Each of the methods described constitutes, in some form or another, an adaptation of the CIE method to suit the technique of television, in accordance with the principles indicated in Chapter 2. In the spectrophotometric method, each sample is defined by a set of numbers representing a spectral distribution of radiance; in the real samples method, coloured surfaces are presented before the camera. In either case, the performance of the camera is determined from the output signal levels obtained with the different samples.

The cameras not considered entirely as "black boxes": four signal processing units require some further consideration, these being the gamma corrector, the matrix circuits (colour correction), the flare corrector and the contour corrector.

The adjustment of the gamma corrector will of course influence the colour rendering since, except in the case where the overall gamma (for the whole television chain) is equal to 1, the relative weight of the colour components is accentuated or diminished by the effect of the power function, thus causing shifts in the displayed colours. The reference display tube gamma is quoted (CCIR Report 624) as being 2.8. In current studio practice, a nominal gamma correction of 0.45 is used in the camera, thus giving an overall system gamma close to 1.3. This gamma slightly above unity gives more pleasing reproduction [10], but means that absolute colour fidelity cannot be achieved. In addition, the camera's gamma corrector is limited in gain near black to avoid excessive amplification of the noise generated within the camera, and this also affects the colour reproduction. For these reasons, it is recommended that colorimetric measurements be carried out assuming an overall response of unity gamma. This assumption is achieved by taking the gammas in both the camera and the display to be unity.

In a practical television camera, non-linearities may occur, even when the gamma corrector is set to unity, owing to the characteristics of the tubes or of the gamma corrector. If these non-linearities cannot be adequately compensated by means of the controls available in the camera, a mathematical correction has to be introduced in the subsequent calculations on the measured signals. Also, the effect of the gamma limitations can be investigated, if required, by introducing the transfer characteristic in subsequent calculations (see Section 7.2).

The matrix in the camera serves to take account, on the one hand, of the difference between the analysis primaries and those in the display and, on the other hand, of the difference between the real analysis curves and those which would be implemented in an ideal situation (including the negative lobes) in seeking to achieve exact reproduction of chromaticities. To give an idea of the colour performance of a camera in practical circumstances, the measurement of the colour rendering should be done, of course, with this matrix in service, although it is also helpful to take measurements with it switched off. In effect, the calculations can be used to optimise the values of the matrix coefficients with a view to obtaining the best possible colour rendering. It may be noted that a variant of the real samples method [11] offers a relatively simple and rapid method of adjusting the colour correction of a camera, through the use of primary signals displayed on an oscilloscope.

Flare can affect the colour rendering. All necessary steps should therefore be taken to limit its effect. In particular, the instructions given for the picture structure and framing in the description of each method should be followed carefully. (The presentation of the samples on a surface of small size in the middle of a large black surround has a determining r81e In this connection.) It is recommended that the flare corrector be switched off whenever possible. It is appreciated that the flare corrector cannot be disabled in all cameras but, as the average picture level produced by the samples is quite low, its influence will normally be am 11

The performance of the contour corrector should be checked (by switching it on and off) to ensure that there is no low frequency component in the correction signal which would affect the colour rendering.

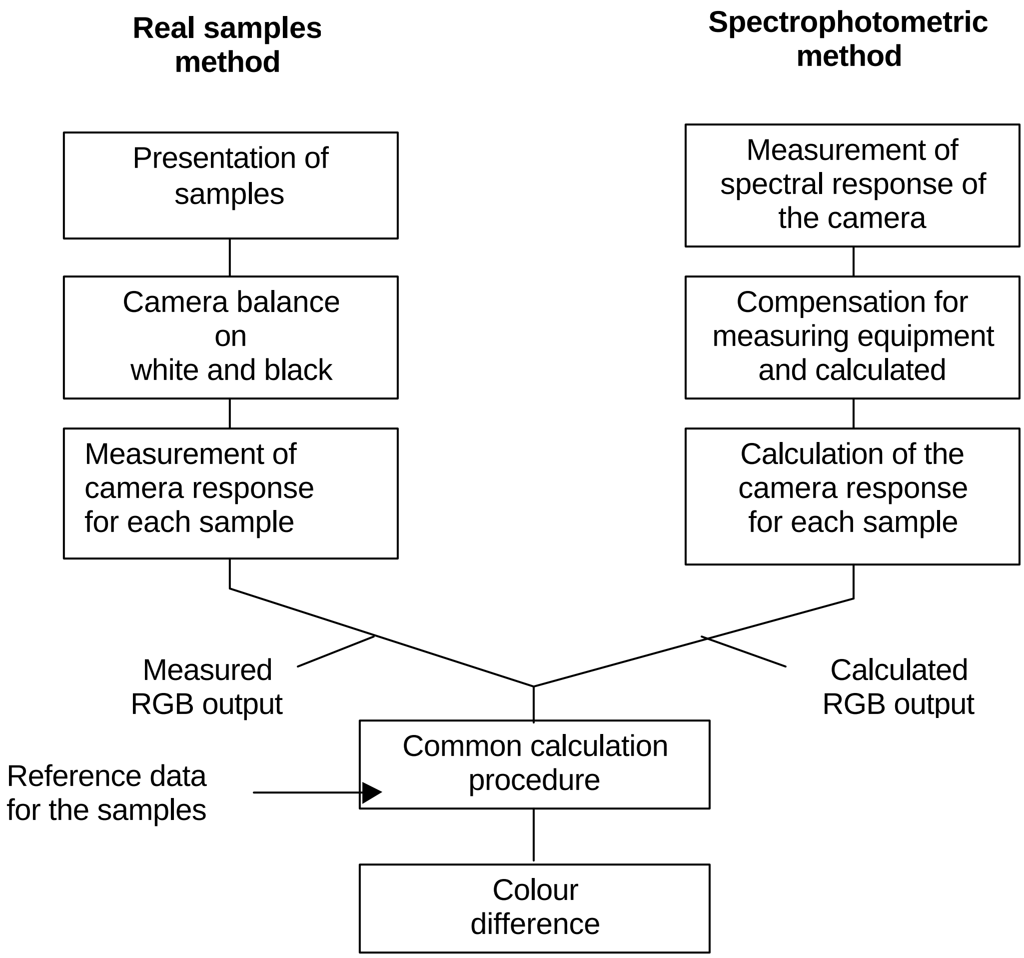
The other sections of the camera, if adjusted to their normal operating positions, will not generally have any effect on the colour performance.

The calculation of the colorimetric quantities is done, in each of the methods that is to be described, on the basis of the values of the camera output signals, whether they be calculated or measured. It is therefore the complete camera, seen as a system, that is being evaluated: the measured response includes the spectral effects of the various sub sections of the camera and, In particular. those of the lens and the pick up tubes. It may be helpful to determine the specific influence of these two elements on the colorimetric quantities as they may have to be replaced during the lifetime of the camera. For large zoom lenses, the transmission factor may vary from one lens to another. However, if they are of the same type and from the same manufacturer, this variation will normally not be sufficient to have any significant effect on the calculations (the difference from the average value will normally be less than ± 1 ΔE^*). There may be a larger difference between lenses of different types from different manufacturers, and it is therefore preferable to measure the camera with the type of lens that is normally to be used with it. Reference can be made to [12] for details of the measurement of lens transmission. It may be noted, furthermore, that an EBU Specialist Group (G/LENSES) is engaged in studies of this question.

The spectral sensitivity of the pick up tube is a predominant factor governing the response to long wavelengths in the red channel. It may also have some effect on the response of the other channels. Therefore, the results will always be related to the particular set of tubes used and, when necessary, new measurements of the response should be made.

The measurements require that certain reference conditions be used. For the presentation of the samples, the so-called 45/0 geometry will be used: sample illuminated at an angle of 45° and viewed perpendicularly (0°) to its surface. This geometry is recommended by the CIE for normal measurements on reflecting samples as it provides, in general, a fairly close measure of the visual effect of the fraction of the incident flux that is reflected diffusely (i.e. excluding the specularly reflected light) by an opaque specimen. The same 4510 conditions are taken into account in the values given for the spectral radiance factors, as used both with the spectrophotometric method and the real samples method.

The flow chart on page 14 indicates the process of successive measurements and computations for the two methods described in Chapters 4 and 5.


Real samples method
Spectrophotometric method
Presentation of samples
Camera balance on white and black
Measurement of camera response for each sample
Measurement of spectral response of the camera
Compensation for measuring equipment and calculated
Calculation of the camera response for each sample
Measured RGB output
Calculated RGB output
Reference data for the samples
Common calculation procedure
Colour difference

CHAPTER 4
The spectrophotometric method

4.1. General description

In this method, the reproduced colour is computed for a certain number of theoretical (imaginary) samples which are defined in terms of their relative spectral energy distribution. It is then compared to the original colour obtained by means of the CIE colour matching functions, in order to determine, as previously indicated, the colour difference &E* for each sample.

To calculate the reproduced colour, the spectral sensitivities of the camera channels are first measured at a number of wavelengths suitably spaced across the visible spectrum (this monochromatic light being produced by a spectrophotometry instrument known as a monochromator). From these measurements, it is possible to calculate the chromaticity co-ordinates for the reproduction of any colour expressed in terms of its spectral energy distribution.

The spectral energy distributions which define the colour samples are obtained by combining the spectral distribution of illuminant D_{65} with appropriately chosen distributions of the radiance factor (see Section 4.7). The relative spectral distribution of illuminant D_{65} has been specified by the CIE [1]; to assist readers, it is reproduced on page 35.

The method is therefore very general and it is not subject to the variations that can be experienced with real samples or their illumination, as regards the stability of their characteristics or the uniformity of their implementation. The samples and the illumination will be exactly the same, for all users and for all time, as they exist only in theory. On account of this, the method is commonly considered as being the fundamental method of colorimetry.

If it is to give satisfactory results, however, it is essential that the initial optical set-up be correct and the various calibrations and opto-mechanical adjustments must be attended to carefully. If the basic calibration is in error, the final results will always be inaccurate, regardless of the excellence of the calculation procedure or the equipment.

4.2. Reference conditions

To some extent, the reference conditions play a part only in the calculations. They do not have to be created by physical means, but care should be taken to ensure that they correspond to a correct theoretical interpretation of the conditions in force for colorimetric measurements.

Unity values of the camera output signals correspond to the reproduction of a reference white. This colour balancing may be obtained by pointing the camera at such a reference white; the equipment and processes described for the real samples method are then used. Balance may also be obtained by computational simulation; details of the corresponding calculations are given in Chapter 6.

4.3. Measurement installation

The narrow bands of wavelengths needed to determine the spectral response of the camera are obtained, as we have said, from a monochromator. This apparatus can take various forms. In Fig. 1, which shows one possible basic measurement arrangement, it is the diffraction phenomenon which is used to obtain the required wavelengths.

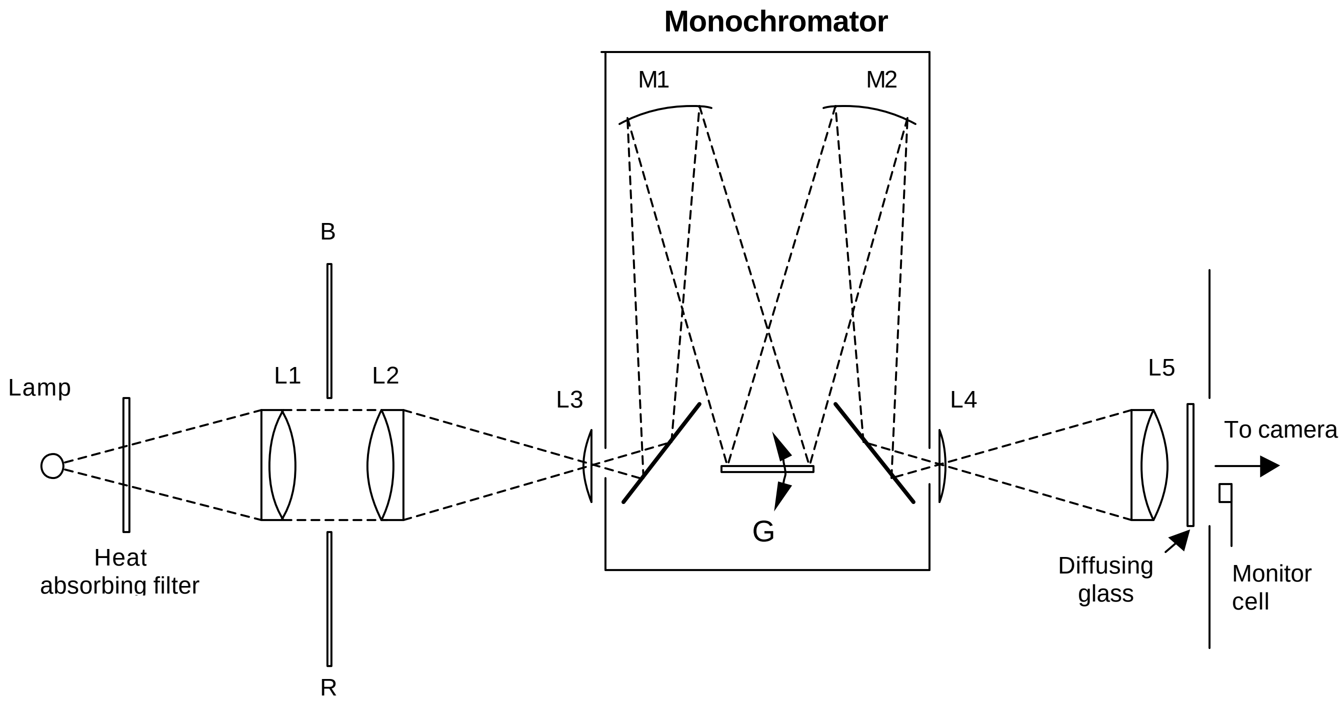


Fig. 1. - Apparatus for spectrophotometric measurements

The beam of white light entering the apparatus via the slit to the right of lens L3, is converted into a parallel beam by mirror M1 and is then spread out into its spectral components by diffraction grating G. Each component wavelength is focussed in the plane of lens L4 by mirror M2. The output slit can be fed by radiation at any part of the spectrum, so that the emerging beam contains, in principle, only the narrow band of wavelengths that is required for a particular measurement.

After the final lens, a diffusing glass is used to create a well-defined surface on which the camera can be focussed and at which the colour of the light produced by the monochromator can be observed. This diffuser can also serve another function (reduction of any polarisation of the light); reference will be made to this at the end of Section 4.4. The video level meter used for the measurements will integrate over a large part of the illuminated area, and the average uniformity over this area is therefore of importance. It is surrounded by a black screen.

Regular measurements will be taken of the energy radiated at each wavelength. The frequency of these checks (before every test, or at longer intervals) will depend on the stability of the equipment characteristics and, above all, of the lamp output. The consistency and accuracy of these measurements are of fundamental importance in determining the overall accuracy of the evaluation of colour fidelity derived from them.

A monitoring cell mounted in front of the diffusing glass is used to measure the energy output. It serves to take into account any spectral variation in the excitation: the data are used to correct the signals measured at the camera output so that they correspond to equal energy illumination.

It has been reported that it should now be possible to obtain silicon cells having a relative calibration accuracy better than + 1% over most of the visible spectrum. To reduce the errors due to this to a minimum, the cell should be purchased from a national standards laboratory specialising in this type of calibration.

4.4. Monochromator calibration and alignment prior to measurements

Before starting the measurements, the monochromator must be calibrated for wavelength, bandwidth and spectral power efficiency. To eliminate any effects of backlash in the control mechanism, the wavelength scan during the initial calibration and during the subsequent measurements must always be made in the same direction.

The range of wavelengths to be considered is that over which the optical system of the camera has a significant response. This is generally taken as being from 380 750 nm. The wavelength calibration of the apparatus may be checked against lasers and gas discharge tubes whose radiation is composed of known wavelengths at different points across the whole visible spectrum.

The bandwidth is a function of the widths of the slits at the entrance and exit ports. These must be large enough to provide sufficient radiant flux for the measurements, but not so large as to introduce errors in those regions where the camera channel response curves exhibit steep slopes. A bandwidth of about 5 nm is recommended. Any variation of the effective bandwidth over the visible spectrum will affect the spectral power distribution of the monochromator and it may be necessary to allow for this effect in the calibration. The bandwidth can be measured using the same laser and gas lines as for wavelength calibration checking.

The monochromatic flux emerging from the instrument will often be polluted by spurious flux of unwanted wavelengths. An effective way of reducing this stray light is to combine two monochromators in series. If only one monochromator is used, the amount of stray light must be checked. If excessive, it can be reduced by the use of baffles and a suitable blue filter (B in Fig. 1) which will block radiation at long wavelengths. The same method can be used to reduce second order diffraction effects (red filter R, which passes only the longer wavelengths).

If the installation is sufficiently reliable to make continual monitoring with the cell unnecessary, correction data can be used in the calculations. The spectral power efficiency of the monochromator may be determined using two monochromators in series: their individual responses and their combined response are measured in turn.. To ensure sufficient stability of the light source (± 0.1%) a form of lamp current stabilisation should be employed.

Having calibrated the monochromator itself, the light source is next calibrated. This can be done in two stages. Firstly, a standard lamp is used to calibrate a photoelectric cell at the output of the monochromator. Then the three components, light source, monochromator and photoelectric cell, are measured together and the calibration for the light source derived from the overall results together with the figures obtained previously for monochromator and photoelectric cell.

The monochromator output may be highly polarised at certain wavelengths. The Presence of polarised light is to be avoided because the separation wavelength of the dichroics of the splitter is clearly influenced by the direction of polarisation. For this reason, cameras are normally fitted with a quarter wave plate in their optical path, this being positioned diagonally (so that the responses to vertically polarised and horizontally polarised light are averaged). If the beam at the output of the monochromator has any appreciable linear polarisation, it should be checked that the direction of polarisation lies at an angle of 45° to the optical akin of this plate. This will cause the linear component to be transformed into circular polarisation; its treatment by the dichroic elements will then be identical to that of non polarised light. Another way of reducing this effect is to fit an opal glass diffuser to the monochromator exit port.

The apparatus should be arranged in such a way that ambient light cannot influence the measurements.

4.5. Camera adjustments prior to measurements

- Switch off the flare corrector (if possible).
- Switch off the contour corrector.
- Set the lens focal length and aperture to values which will prevent any significant amount of vignetting.
- Adjust the black and white shading correctors to the optimum position.
- Set the gamma to 1 and check that this value is effectively realised. If this cannot be done, the measurements should be taken using a probe at a point in the camera where the gamma is unity.
- Adjust the black balance and level on a reference black as described for the real samples method (Section.5.4).
- For the measurements with the matrix in service, a considerable amount of lift (about 20%) is to be introduced, so as to avoid clipping of the signals corresponding to the negative lobes of the spectral curves, which may be produced with monochromatic light.
- Adjust the white balance and level on a white reference as described for the real samples method (Section 5.5)

- Check that no significant change is observed in black or white balance with the matrix in or out of service, or with the contour correction in or out (if a difference greater than about 0.5% is observed, the matrix should be checked).
- Verify the grey scale tracking.

An exact adjustment of black or white balance is not needed when this is made by computation afterwards. If this is the case, measurements with matrix in service require that the matrix coefficients be known. These coefficients can be determined by measurements of the camera outputs at three particular wavelengths, one in each of the red, green and blue regions, where only one tube has an output. Alternatively, electrical measurements may be made on the matrix itself.

4.6. Measurement procedure

The camera is positioned so that its optical axis is normal to the diffusing glass and it is focussed on the glass.

The focal length is adjusted so that the illuminated area occupies about 10% of the picture, in the central area. The rest is filled with a black surround (which should extend somewhat outside the picture area).

Care should be taken to exclude extraneous light from the set up. Fluorescent lights, monitor CRTs and neon indicators are common sources of interference.

The measurements are taken with a video level meter (integrating over an area giving the best compromise between the effects of noise and non-uniformity). A low-pass filter (~ 0.5 MHz) may help to reduce the effect of noise in the measurement channel. Subsequent correction for the light source will magnify any errors in the blue and it may prove beneficial to take the average of a number of readings at each wavelength, particularly in this region.

The measurements begin with a sweep across the entire visible spectrum to verify that the channel gains are set to give reasonable maximum signal levels in each channel.

Each monochromatic radiation is then analysed, the spectrum being scanned in 10 nm steps (greater accuracy can be obtained for the steep slopes of the response curves if steps of 5 nm are adopted). The signal levels at the main camera outputs and the monitoring cell output, are measured for each wavelength (if the equipment is sufficiently stable, the monitoring cell output does not have to be measured in every test).

4.7. Choice of theoretical samples

The choice of colour samples, like the application of reference conditions, has to be taken into account at the calculations level only.

To be representative of actual practice, any method must be based on the conditions that exist in reality. In television work, the colours that have to be reproduced are, for the most part, surface colours and it is for such colours that a wide variety of examples of spectral energy distribution are available (spectral radiance factors). It is therefore logical to define the theoretical samples on the basis of the coloured objects to which it Is required that they should correspond. It is recommended that the same samples as for the real samples method are used the first instance, in order to ensure correlation between the two methods.

In Appendix 3, there is a list showing the spectral radiance factors corresponding to a choice of real samples. Other sets of radiance factors established to suit the required spectral characteristics can, of course, be used.

4.8. Choice of illumination for the samples

The characteristics of this illumination do not affect the measurement procedure, although they do have a role to play in the subsequent calculation of the camera response. The illumination is nonetheless the same as that which served in balancing the camera (Section 4.2). If this balance has been established using a reference white, the real spectrum of the illumination must be measured; if it is simulated by calculation the (theoretical) illumination will normally be typical studio lighting.

CHAPTER 5
The real samples method

5.1. General description

Subjectively, the colour fidelity of a camera is judged in practice by observing how well it reproduces the colours of a scene. The real samples method is a direct interpretation of this approach. It has been devised as a simplified representation of real operational conditions and it is this aspect which constitutes its principal advantage.

In this method, the camera is directed towards a number of coloured samples which are normally shown to the camera in turn. The measurement of the reproduction quality is given for each of them by the calculated value of the colour difference between the reproduced and original colours.

As for the method using theoretical samples, the original colour of each sample is obtained from its spectral radiance factor and from the spectral energy distribution of illuminant D_{65}. The relative spectral distribution of illuminant D_{65} has been specified by the CIE [1] and, for the benefit of the reader, it is reproduced later in this document (p. 35). The spectral radiance factor of the samples is measured using a spectrophotometer. This method, like the others, is therefore based on spectrophotometric and spectroradiometric measurements. To check the measuring apparatus, coloured ceramic tiles are available which are particularly stable and which are calibrated with extreme accuracy (see Appendix 3). It will be noted, however, that it is not essential to have a spectrophotometer available before the real samples method can be used, as certain samples manufacturers supply details of the spectral characteristics with their products. Care should be taken to have these data regularly re checked (for example, once a year).

The reproduced colour is calculated, for each sample, on the basis of the values of the signals at the camera output. Accurate measuring equipment is essential here: in effect, a mathematical analysis shows that even a small error in the measured values will have a large effect on the final results.

A large number of factors are involved in the implementation of this method and their influence is not always known with any degree of certainty. In general, the greatest care must be taken, therefore, in preparing the measurements. To eliminate these uncertainties and to facilitate the implementation of the method, consideration has been given to the possibility of using an automatic system to show the samples to the camera. In this system, the measurement installation, which is mounted on a chassis, carries (as shown in Fig. 2) two calibrated light sources directing light at a fixed angle onto a device serving to show all the colour samples in identical conditions and to verify the measurements on basic colour references such as a plaque of barium sulphate or calibrated ceramic tiles. The description of this apparatus is given in Appendix 4.

The procedure for calculating the results from the measured values is relatively simple and can be effected using a small programmable calculator.

5.2. Illumination of the samples

The light source recommended by the CIE for the determination of colour differences is illuminant D_{65}. Furthermore, the white reproduced by the television system should match this illuminant. These two reasons would suggest the use of such an illuminant for lighting the samples. However, this theoretical source is difficult to simulate satisfactorily with any real light (although it is possible to make a source approaching this simulation and methods exist for calculating the degree of approximation of such a source to D_{65}. [13]). Also, the internal circuits of a camera are designed to compensate for any difference between this white and a white which, for studio work, is conventionally 3200 K. (To increase lamp life, a lower figure is used in practice in studios.) In daylight camera work, a colour temperature conversion filter is inserted in the optical path, so that the same colour temperature is also normally used outdoors. It therefore seems more appropriate to adopt the "studio" type of lighting to illuminate the samples.

The sources of light simulating studio illumination should have a correlated colour temperature of 3100 K ± 100 K. The tolerance takes into account both the inaccuracy in the definition and production of the illuminant and of the range of colour temperatures which will, in any case, have a negligible effect on the results of the calculation. Either calibrated low voltage halogen lamps or special reference lamps can be used to obtain the required colour temperature (see Appendix 2).

Stability of the lighting is a basic requirement if reliable results are to be obtained. Therefore a regulated supply should be used for the lamps. If the light flux from an incandescent lamp is to be constant to within better than + 0.5% the current stabilisation, and therefore the power supply regulation. must be within + 0.1%.

The level of the illumination will depend on the sensitivity of the cameras to be examined. Levels between 1000 and 1500 lx are commonly used.

5.3. Lighting and viewing geometry

The positions of the various parts of the installation are shown in Fig. 2. According to the CIE specifications, the light source must illuminate the sample at an angle of 450 to the normal through the sample (a tolerance of ± 5° is acceptable). To ensure that the illumination is sufficiently uniform, the light will come from both sides.

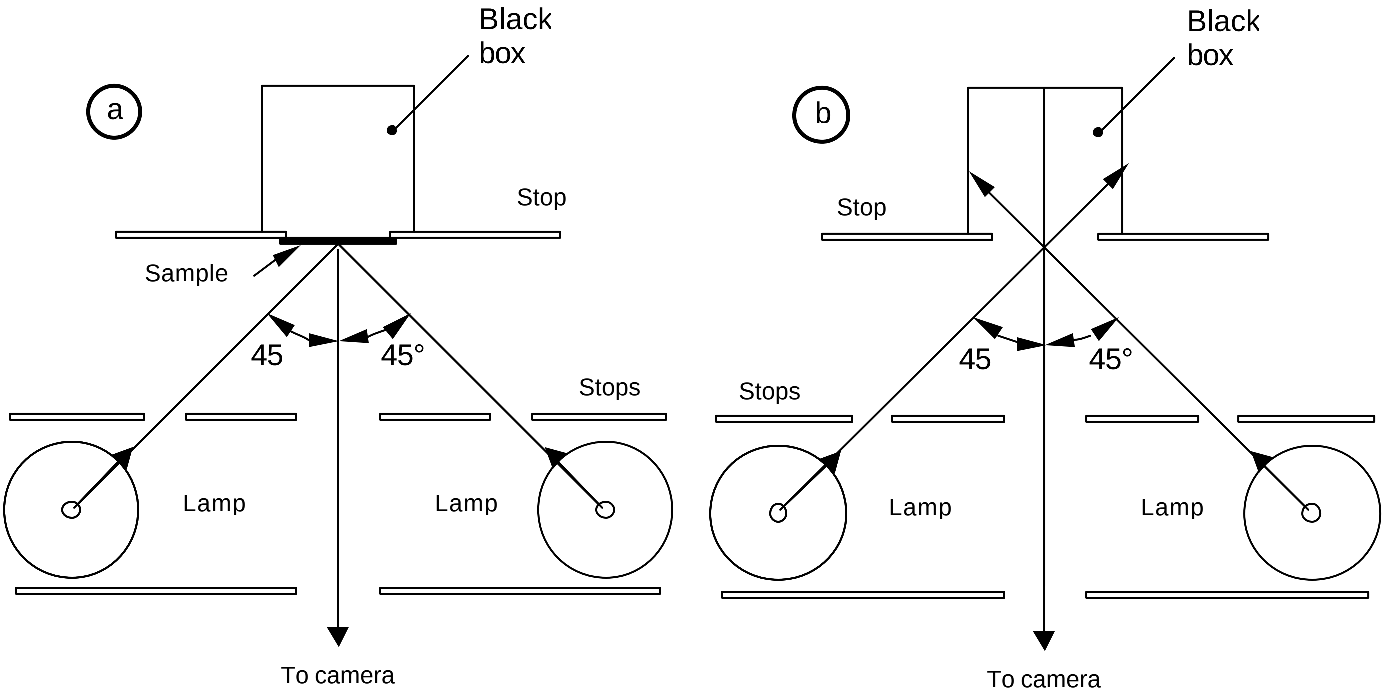


Fig. 2. - Geometry of samples presentation

The stops shown in the diagram serve to limit the beams of light so that only the surface of the sample itself is lit. In the CIE specification, the angle between the axis and any ray of an illuminating beam should not exceed 5°. The optical axis of the camera is positioned normal to the surface of the sample (within ± 5°) and the field of vision is limited by another stop so that only the surface of the sample is seen by the camera.

5.4. Black reference

As a black reference, a box of adequate depth covered on the inside with black velvet (or some other material of low reflectance) can be placed behind an opening positioned in the place normally occupied by the samples.

5.5. White reference

A plaque of barium sulphate ($BaS0_4$) in pressed powder form is recommended as the reference white. The surface of such a plaque has a reflectance of 100% and it is the reference currently recommended by the CIE for colorimetric measurements. As can be seen in Appendix 1, this reference can be made up by the user with the aid of an appropriate pressing device. It can also be purchased. In the former case, care should be taken to follow the recommendation for use of the powder to ensure a consistent response. The reference should be checked regularly, at intervals depending on the use made of it (for example, once a year).

There are other more practical forms of reference white. Some information about them is given in Appendix 1. Provided that the differences between their characteristics and those of $BaS0_4$ are known, these can be used in routine measurements, with a suitable correction being made during the calculations.

5.6. Colour samples

If it is to be representative, the collection of real samples should contain colours that are well distributed over the most important area of the colour diagram, within the triangle formed by the EBU primaries. This collection must also contain colours which, in spectral terms, are representative of object colours commonly encountered in television scenes. This criterion is especially Important for well known colours such as flesh tones, the colours of hair, grass, foliage, foodstuffs, fruits, etc., for which viewers tend to be especially critical as regards the reproduced colour.

The colorimetric data of the real samples will normally vary somewhat from one production batch to another, as well as with age on account of handling and exposure to light. Each batch must therefore be supplied with calibration data and this should be checked after the samples have been used for any length of time. The most accurate method for checking the samples involves the use of a spectrophotometer. It may be convenient to have two sets of samples, one for normal measurements and the other for occasional comparative checks on the first. By this means, the changes caused by handling, accumulation of dust, etc. can be determined. The eye is a very sensitive detector of colour differences when the samples are seen side-by-side and it may be expected that a simple visual inspection will give very adequate comparisons. It is preferable to inspect the two sets of samples (assumed equal when new) under both incandescent light and daylight.

In addition to covering a range of chromaticities with the samples, it is also desirable to have a range of luminance values. The spectral response characteristics of the camera may vary according to the signal level, owing to non-linearities. Pairs of samples with similar chromaticities but different luminance values will serve to show up any such effects. It may also be helpful to have a set of highly saturated colours.

A reasonably complete picture of the colour performance of a camera will require the use of about twenty samples. It might, of course, be advantageous to use even more.

Appendix 3 gives the data corresponding to one possible collection of samples. In order to avoid introducing too many new colours, the collection is made up very largely of samples that are commercially available and which have already been used for television camera colorimetry. By this means comparisons with earlier results can be made.

The EBU is currently examining the possibility of standardising a set of samples. Studies (such as [14]) have been directed towards this goal.

5.7. Camera adjustments prior to measurements

The camera is positioned in such a way that its optical axis coincides (± 5°) with the perpendicular through the centre of the samples.

- Switch off the flare corrector (if possible).
- Switch off the contour corrector.
- Set the lens focal length and aperture to values suitable to prevent significant vignetting.
- Adjust the white and black shading correctors to the optimum position.

- Set the gamma to 1 and check that this value is effectively realised. If this cannot be done, measurements should be taken, using a probe, at a point in the camera where the gamma is unity.
- Adjust the black balance and level on the black reference in order to obtain a signal level of 35 mV (5%) at the main signal outputs.
- Adjust the white balance and level on the white reference to obtain a signal level of 700 mV (100%) at all the main signal outputs, ensuring that the white clippers have no effect.
- It should be recalled that the reference white must be uniformly illuminated by a light source having a correlated colour temperature of 3100 ± 100 K and that the level of illumination should be between 1000 and 1500 lx.
- Check that no significant change is observed in the white or black balance with the matrix in or out of use, or with the contour correction in or out (if any difference greater than 0.5% is observed, the matrix must be checked).
- Verify the grey scale tracking in these conditions.

5.8. Measurement procedure

It is assumed that the measurement installation conforms to the general arrangement shown in Fig. 2 (and Appendix 4). It will also be assumed that no stray light falls on the sample surface and that the camera is adjusted as mentioned above.

The lamp current is adjusted to its calibrated value, which is to be maintained throughout the colorimetric measurements. Voltages and currents should be measured with an instrument of accuracy conforming to Appendix 2.

The white surface of barium sulphate is placed in the opening of the black box, in the same position as that adopted by the samples, as shown in Fig. 2a. It is used to adjust the white balance of the camera and to set the peak white of all the channels to 700 mV, as mentioned in Section 5.7.

The camera is focussed on the sample and the zoom is adjusted to a mid-range setting so that the surface of the reference (and of the samples) appears in the centre of the image and occupies 10% of the entire picture area.

The samples are then placed in turn in the same position as the reference. The main R, G, B (or W, R, B) signal outputs are measured, first without the electronic matrix in service and then with matrix.

The measurements are taken with a differential oscilloscope or, better still, with a video level meter (care should be taken to use an integration area that is no greater than that which is absolutely necessary). The measurement accuracy must be at least + 0.5%. To minimise the influence of noise, a low pass filter (~ 0.5 MHz) should i.e. inserted in the measurement chain (care must be taken to avoid introducing any appreciable phase distortion).

In order to avoid the effects of any possible instability of the performance of the camera, the balance of the camera should be regularly verified on the reference white (for example, after each measurement on a sample).

CHAPTER 6
Basic calculation procedure

The camera response, measured or calculated in accordance with the instructions given earlier, is converted into CIE colour parameters by calculation. The direct evaluation of a camera from the measured or calculated response would, at beet, give only a very approximate idea of its performance, unless information has first been gathered on the visual Importance of the relative variations in R, G, B. In fact, information such as this is built into the CIE method.

The formulas and the procedures presented here may sometimes appear rather complex, but their detailed explanation is intended merely to assist the reader in compiling suitable programs for an electronic calculator.

The basic procedure described here is directly applicable to a camera with unity gamma giving primary RGB signals at its outputs.

Symbols used

$R(A)_n$, $G(A)_n$, $B(A)_n$	Primary signal values (in mV) for sample n, measured with respect to blanking level (blanking level = 0%, white level = 100%)
A	Black lift (in mV)
R_n , G , B_n	Primary signal values (in mV) for sample n, corrected for gamma and black level ($g = 1$, black level = 0%, white level = 100%)
$R(e)_l$, $G(e)_l$, $B(e)_l$	Relative spectral response, corrected to refer to equal energy input
A(0)	Reference level for spectrophotometric measurements after the matrix
u'_{0n}, v'_{0n}	Chromaticity co-ordinates, in the CIE 1976 chromaticity diagram, of the original colour of sample n, under illuminant D_{65}

x_0, y_0, z_0	Tristimulus values, in the CIE 1931 colour space, of the reference white, under illuminant D_{65}
u'_0, v'_0.	Chromaticity co-ordinates, in the CIE 1976 chromaticity diagram, of illuminant D_{65} or reference white
X_n, Y_n, Z_n	Tristimulus values, in the CIE 1931 colour space, of the reproduced colour of sample n
u'_n, v'_n	Chromaticity co-ordinates, in the CIE 1976 diagram, of the reproduced colour of sample n
$\bar{x}_l$, $\bar{y}_l$, $\bar{z}_l$	CIE colour matching functions for a 2° field (and equal energy illuminant)
$\bar{r}_l$, $\bar{g}_l$, $\bar{b}_l$	Colour matching functions in the EBU R, G, B system (for a 2° field and equal energy illuminant)
S_l	Spectral energy distribution of the light source
k	A factor used to normalise the response on reference white
L*u*v*	Coordinates in the CIE 1976 L*u*v* (CIELUV) colour space
ΔE^*	The total difference (shift) ΔE^*_{uv} between the original and reproduced colours, in the CIELUV colour space

6.1. Calculation of the parameters characterising the camera response

This Section gives details of calculations which are different in the spectrophotometric and the real samples methods.

Spectrophotometric method

As shown in Section 4.5, it is first necessary to ensure that the black level is sufficiently high to prevent clipping of the negative lobes of the camera response. Let the black lift in channel (i) be equal to A(i). In practical terms, this lift corresponds to a signal at the output of channel (i) at the edge of the visible spectrum (750 nm).

The measured signals for the various monochromatic radiations R_{ml}, G_{ml}, B_{ml} are corrected as follows:

$$R_l = R_{ml} - A(r)$$

$$G_l = G_{ml} - A(g)$$

$$B_l = B_{ml} - A(b)$$

These values must then be corrected to take account of variations in the energy level at the output of the monochromator; the data derived from its calibration, or from the monitoring cell, are used for this purpose. This signal must itself be corrected to take account of the known variation of the spectral sensitivity of the cell, this being found by calibration, in order to obtain a valid indication of the relative energy leaving the monochromator.

The relative spectral response of each of the three channels is obtained, at each wavelength produced by an equal energy source, by dividing the value of the camera signal by that of the relative energy of the monochromator.

Let $R(m)_l$, $G(m)_l$, $B(m)_l$ designate this response.

The camera must then be balanced for the scene illuminant in use. For measurements without matrix, this can be done directly; the operation is effected on signals $R(e)_l = R(m)_l$ etc. For measurements with matrix, the balancing must be done on the signals at the input to the matrix. It is therefore necessary to start by eliminating the effect of the matrix. This is done by calculating the matrix coefficients, for example from measurements taken at three wavelengths for which only one of the camera tubes produces an output signal. The effect of the matrix is then eliminated by simple linear algebra. If M is the matrix in question, the signals before the matrix are deduced using the equation:

$$\begin{vmatrix} R(e)_l \\ G(e)_l \\ B(e)_l \end{vmatrix} = M^{-1} . \begin{vmatrix} R(m)_l \\ G(m)_l \\ B(m)_l \end{vmatrix}$$

It is then possible to calculate the overall response of each channel for a sample n having spectral radiance factor P.A,, and illuminated by a source having a relative spectral energy distribution equal to SX (the calculation is the same whether or not the matrix is in service during the measurements).

$$R_n = k_R \sum_{380}^{750} S_l .b_{ln}.R(e)_l \qquad k_R = \frac{1}{\sum_{380}^{750} S_l .R(e)_l}$$

$$G_n = k_G \sum_{380}^{750} S_l .b_{ln}.G(e)_l \qquad k_g = \frac{1}{\sum_{380}^{750} S_l .G(e)_l}$$

$$B_n = k_B \sum_{380}^{750} S_l .b_{ln}.B(e)_l \qquad k_B = \frac{1}{\sum_{380}^{750} S_l .B(e)_l}$$

The correction factors k_R, k_G, k_B are such that $R_W = G_W, = B_W = 1$ for the reference white. The physical operation to which these formulas correspond is that of balancing the camera on a reference white with a spectral distribution S_l. The formulas giving R_n, G_n, B_n correspond to adjustments of the camera gains as a result of this balancing, the value obtained during balancing being taken as unity for each channel. The spectral distribution S_l to be considered here is normally that of illuminant P 3100 (Table 1, p. 34), which represents studio lighting. It may be illuminant D_{65} (Table 2, p. 35) or some other representation of daylight if the corresponding filters and operational matrices have been introduced in the camera before the measurements are taken.

Appendix 3 shows some examples of spectral distribution b_l of the radiance factors for a selection of colour samples.

The values R., G., B. constitute the overall response at the output of the three channels when these measurements are taken without matrix.

$$R_{Tn} = R_n$$

$$G_{Tn} = G_n$$

$$B_{Tn} = B_n$$

For measurements taken with matrix, the effect of the matrix now has to be taken into account, In order to obtain the overall response

$$\begin{vmatrix} R_{Tn} \\ G_{Tn} \\ B_{Tn} \end{vmatrix} = M \cdot \begin{vmatrix} R_n \\ G_n \\ B_n \end{vmatrix}$$

Real samples method

The primary signals $R(A)_n$, $G(A)_n$, $B(A)_n$ are normally measured, in mV, by assuming that blanking has the value zero. In colorimetric calculations, it Is their amplitude above black level which has to be considered and the measured values are therefore corrected according to the value A (in mV) of the black level. They are then transformed into percentages of peak white amplitude. These two operations can be performed by the formulas:

$$R_n = \frac{R(A)_n - A}{7000 - A} 100$$

$$G_n = \frac{G(A)_n - A}{7000 - A} 100$$

$$B_n = \frac{B(A)_n - A}{7000 - A} 100$$

If we wish to examine the effect of the matrix, the same formulas as are used in the spectrophotometric method can be used, in conjunction with measurements taken without matrix. Let R_{n1}, G_{n1}, B_{n1} represent the values obtained without matrix.

Balancing of the three channels on the white, at this point in the chain, gives the values R_w, G_w, B_w.

The effect of the matrix is obtained by calculating:

$$\begin{vmatrix} R_n \\ G_n \\ B_n \end{vmatrix} = M \cdot \begin{vmatrix} R_{n1}/R_w \\ G_{n1}/G_w \\ B_{n1}/B_w \end{vmatrix}$$

6.2. Calculation of the colorimetric parameters characterising the reproduced reference colour

The colour defined by the components of the camera output signal now has to be expressed in colorimetric parameters taking account of the characteristics of the standard colorimetric observer for a 2° field. In other words, the values R_n, G_n, B_n, obtained for each sample n must be converted into values of X, Y, Z in the CIE 1931 colorimetric reference system. Furthermore, the reproduction primaries are those of the EBU [6] which differ from those of the CIE. Since the equal-signal white is D_{65}, an overall matrix could be established which will convert from values of R_n, G_n, B_n, into values X_n, Y_n, Z_n,. The formula for this conversion is:

$$\begin{vmatrix} X_n \\ Y_n \\ Z_n \end{vmatrix} = \begin{vmatrix} 0.4306 & 0.3416 & 0.1782 \\ 0.2220 & 0.7067 & 0.0713 \\ 0.0202 & 0.1296 & 0.9392 \end{vmatrix} \cdot \begin{vmatrix} R_n \\ G_n \\ B_n \end{vmatrix}$$

From this, the u'_n, v'_n co-ordinates in the CIE 1976 diagram are deduced:

$$u'_n = \frac{4X_n}{X_n + 15Y_n + 3Z_n}$$

$$v'_n = \frac{4Y_n}{X_n + 15Y_n + 3Z_n}$$

It is then possible to calculate the L*, u*, v* coordinates of the reproduced colour in the CIELUV 1976 space. These co-ordinates will then be used to determine the colour difference.

$$L^*_n = 116(Y_n / Y_0)^{1/3} - 16$$

$$u^*_n = 13L^*_0\,(u'_n - u'_0)$$

$$v^*_n = 13L^*_0\,(v'_n - v'_0)$$

In these last formulas, the values given the suffix 0 relate to the reference white (D_{65}). They have the following values:

$$Y_0 = 1$$

$$u'_0 = 19.78$$

$$v'_0 = 46.83$$

The formula giving L^*_n is valid only for $(Y_n / Y_0) > 0.01$; this condition is normally satisfied with the available samples.

It should be noted that the luminance factor L^*_n used in the calculation of u* and v* is purely empirical and its use in television should perhaps be considered tentative.

6.3. Calculation of the calorimetric parameters characterising the original reference colour

The triatimulus values X_{0n} , Y_{0n} , Z_{0n} of the original colour of sample n, illuminated by D_{65}, can be determined immediately, without passing via the primaries R, G, B.

If S_l is the spectral energy distribution of this illuminant and b_{ln} , the spectral radiance factor of the sample, these co-ordinates are given by:

$$X_{0n} = k_g \sum_{380}^{750} S_{ln}.b_{ln}.\bar{x}_l$$

$$Y_{0n} = k_g \sum_{380}^{750} S_{ln}.b_{ln}.\bar{y}_l$$

$$Z_{0n} = k_g \sum_{380}^{750} S_{ln}.b_{ln}.\bar{z}_l$$

In these formulas, the symbols $\bar{x}_l$, $\bar{y}_l$, $\bar{z}_l$ designate the colour-matching functions for the CIE 1931 standard observer (2° field) and

$$k_l = \frac{1}{\sum_{380}^{750} S_l.\bar{y}_l}$$

in order that Y will have the value 1 (or 100%) for the reference white.

Then, using the same formulas as are given above, the co-ordinates U'_{0n} , v'_{0n} of the original colour are calculated in the CIE 1976 diagram, followed by the L^*_{On}, u^*_{0n}, v^*_{0n} co-ordinates of this colour in the CIELUV 1976 colour space.

Note

The expression "ideal spectral response" of a camera is sometimes used, this implying a response such that the reproduced colour is equal to the original colour under illuminant D_{65}. It can be shown that, when the illuminant is D_{65}, the ideal response is given by the colour-matching functions TA, ils SA for the EBU primaries.

$$R_{0l} = \bar{r}_l$$

$$G_{0l} = \bar{g}_l$$

$$B_{0l} = \bar{b}_l$$

In the general case where spectral energy distribution S_l of the studio illumination differs from D_{65} the ideal response is given by

$$R_{0l} = \frac{D_{65l}}{S_l}\bar{r}_l \qquad G_{0l} = \frac{D_{65l}}{S_l}\bar{g}_l \qquad B_{0l} = \frac{D_{65l}}{S_l}\bar{b}_l$$

6.4. Calculation of the colour difference

The colour difference ΔE^*_n is finally calculated:

$$\Delta E^*_n = \left[\Delta L^{*2}_n + \Delta u^{*2}_n + \Delta v^{*2}_n\right]^{1/2}$$

where ΔL^*_n, Δu^*_n, Δv^*_n are the differences between the values of the co-ordinates L^*_n, u^*_n, v^*_n for the original and reproduced reference colours for sample n.

$$\Delta L^*_n = L^*_n - L^*_{0n}$$

$$\Delta u^*_n = u^*_n - u^*_{0n}$$

$$\Delta v^*_n = v^*_n - v^*_{0n}$$

As shown in Chapter 2, the representation of colour in the L*u*v* space is similar to that adopted In the Munsell classification. This means that the two types of colour representation can be associated. In particular, it is possible to measure the parameters used in the Munsell system: lightness, chroma and hue. By this means, a "CIE 1976 psychometric lightness", a "CIE 1976 chroma", a "CIE 1976 hue angle" and a "CIE 1976 hue difference" are defined [15].

The value L^* is a measure of the lightness; it is referred to as the "psychometric lightness".

The perceived chroma (or colourfulness) is measured by:

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

The perceived hue is measured in the form of the hue angle:

$$h = \arctan\left(v^* / u^*\right)$$

The concept of hue difference has been introduced as a means of separating the colour difference into orthogonal components; it is defined by:

$$\Delta H^* = \left[\Delta E^{*2} - \Delta L^{*2} - \Delta C^{*2}\right]^{1/2} \qquad \text{where } \Delta C^* = C^*_n - C^*_{0n}$$

6.5. Some calculated results to be presented

1. The luminance factor Y and the chromaticity co-ordinates u'_n , v'_n in the CIELUV colour space, for all the samples
2. The colour difference ΔE^*_i in the CIELUV colour space for each sample, except for the neutral ones; the chroma difference ΔC^* and the hue difference ΔH^* for all the samples.
3. The average difference ΔE^*_a for the de-saturated samples; the average difference ΔE^*_a for all the samples.
4. The result for the least favourable colour.
5. The mean square deviation of the values of ΔE^*_i for the desaturated samples; the mean square deviation of ΔE^*_i for all the samples.

The above data relate equally well to the physical samples as used in the real samples method as they do to the spectral data used in the spectrophotometric method.

Table 1, Relative spectral energy distribution of Illuminant P 3100

l (nm)	S_l	*l* (nm)	S_l
380	0.13706	580	1.11674
385	0.15045	585	1.14559
390	0.16463	590	1.17424
395	0.17959	595	1.20269
400	0.19532	600	1.23091
405	0.21183	605	1.25887
410	0.22911	610	1.28656
415	0.24714	615	1.31397
420	0.26593	620	1.34106
425	0.28545	625	1.36782
430	0.30569	630	1.39424
435	0.32664	635	1.42031
440	0.34826	640	1.44600
445	0.37055	645	1.47130
450	0.39347	650	1.49620
455	0.41701	655	1.52070
460	0.44113	660	1.54477
465	0.46581	665	1.56841
470	0.49103	670	1.59160
475	0.51674	675	1.61435
480	0.54293	680	1.63664
485	0.56955	685	1.65846
490	0.59659	690	1.67981
495	0.62400	695	1.70069
500	0.65176	700	1.72108
505	0.67982	705	1.74099
510	0.70817	710	1.76041
515	0.73677	715	1.77933
520	0.76558	720	1.79776
525	0.79457	725	1.81570
530	0.82371	730	1.83314
535	0.85297	735	1.85007
540	0.88232	740	1.86652
545	0.91173	745	1.88246
550	0.94116	750	1.89790
555	0.97059	755	1.91285
560	1.00000	760	1.92731
565	1.02934		
570	1.05859		
575	1.08774		

Table 2. - Relative spectral energy distribution of Illuminant D_{65}

l (nm)	S_l
380	0.49976
385	0.52312
390	0.54648
395	0.68702
400	0.82755
405	0.87120
410	0.91486
415	0.92459
420	0.93432
425	0.90057
430	0.86682
435	0.95774
440	1.04865
445	1.10936
450	1.17008
455	1.17410
460	1.17812
465	1.16337
470	1.14861
475	1.15392
480	1.15923
485	1.12367
490	1.08811
495	1.09083
500	1.09354
505	1.08578
510	1.07802
515	1.06296
520	1.04790
525	1.06240
530	1.07689
535	1.06047
540	1.04405
545	1.04226
550	1.04046
555	1.02023
560	1.00000
565	0.98167
570	0.96334
575	0.96061

l (nm)	S_l
580	0.95788
585	0.92237
590	0.88686
595	0.89346
600	0.90006
605	0.89803
610	0.89599
615	0.88649
620	0.87699
625	0.85494
630	0.83289
635	0.83494
640	0.83699
645	0.81863
650	0.80027
655	0.80121
660	0.80215
665	0.81246
670	0.82278
675	0.80281
680	0.78284
685	0.74003
00	0.69721
695	0.70665
700	0.71609
705	0.72979
710	0.74349
715	0.67977
720	0.61604
725	0.65745
730	0.69886
735	0.72486
740	0.75087
745	0.69340
750	0.63593
755	0.55005
760	0.46418
765	0.56612
770	0.66805

Table 3. - Spectral tristimulus values for the CIE 1931 standard colorimetric observer and the CIE XYZ primaries

l (nm)	$\bar{x}(l)$	$\bar{y}(l)$	$\bar{z}(l)$	l (nm)	$\bar{x}(l)$	$\bar{y}(l)$	$\bar{z}(l)$
380	0.0014	0.0000	0.0065	580	0.9163	0.8700	0.0017
385	0.0022	0.0001	0.0105	585	0.9786	0.8163	0.0014
390	0.0042	0.0001	0.0201	590	1.0263	0.7570	0.0011
395	0.0076	0.0002	0.0362	595	1.0567	0.6949	0.0010
400	0.0143	0.0004	0.0679	600	1.0622	0.6310	0.0008
405	0.0232	0.0006	0.1102	605	1.0456	0.5668	0.0006
410	0.0435	0.0012	0.2074	610	1.0026	0.5030	0.0003
415	0.0776	0.0022	0.3713	615	0.9384	0.4412	0.0002
420	0.1344	0.0040	0.6456	620	0.8544	0.3810	0.0002
425	0.2148	0.0073	1.0391	625	0.7514	0.3210	0.0001
430	0.2839	0.0116	1.3856	630	0.6424	0.2650	0.0000
435	0.3285	0.0168	1.6230	635	0.5419	0.2170	0.0000
440	0.3483	0.0230	1.7471	640	0.4479	0.1750	0.0000
445	0.3481	0.0298	1.7826	645	0.3608	0.1382	0.0000
450	0.3362	0.0380	1.7721	650	0.2834	0.1070	0.0000
455	0.3187	0.0480	1.7441	655	0.2187	0.0816	0.0000
460	0.2908	0.0600	1.6692	660	0.1649	0.0610	0.0000
465	0.2511	0.0739	1.5281	665	0.1212	0.0446	0.0000
470	0.1954	0.0910	1.2876	670	0.0874	0.0320	0.0000
475	0.1421	0.1126	1.0419	675	0.0636	0.0232	0.0000
480	0.0956	0.1390	0.8130	680	0.0468	0.0170	0.0000
485	0.0580	0.1693	0.6162	685	0.0329	0.0119	0.0000
490	0.0320	0.2080	0.4652	690	0.0227	0.0082	0.0000
495	0.0147	0.2586	0.3533	695	0.0158	0.0057	0.0000
500	0.0049	0.3230	0.2720	700	0.0114	0.0041	0.0000
505	0.0024	0.4073	0.2123	705	0.0081	0.0029	0.0000
510	0.0093	0.5030	0.1582	710	0.0058	0.0021	0.0000
515	0.0291	0.6082	0.1117	715	0.0041	0.0015	0.0000
520	0.0633	0.7100	0.0782	720	0.0029	0.0010	0.0000
525	0.1096	0.7932	0.0573	725	0.0020	0.0007	0.0000
530	0.1655	0.8620	0.0422	730	0.0014	0.0005	0.0000
535	0.2257	0.9149	0.0298	735	0.0010	0.0004	0.0000
540	0.2904	0.9540	0.0203	740	0.0007	0.0002	0.0000
545	0.3597	0.9803	0.0134	745	0.0005	0.0002	0.0000
550	0.4334	0.9950	0.0087	750	0.0003	0.0001	0.0000
555	0.5121	1.0000	0.0057	755	0.0002	0.0001	0.0000
560	0.5945	0.9950	0.0039	760	0.0002	0.0001	0.0000
565	0.6784	0.9786	0.0027	765	0.0001	0.0000	0.0000
570	0.7621	0.9520	0.0021	770	0.0001	0.0000	0.0000
575	0.8425	0.9154	0.0018				

Table 4: - Spectral tristimulus values for the CIE 1931 standard colorimetric observer and the EBU RGB primaries

l (nm)	$\bar{x}(l)$	$\bar{y}(l)$	$\bar{z}(l)$	l (nm)	$\bar{x}(l)$	$\bar{y}(l)$	$\bar{z}(l)$
380	0.001	-0.001	0.007	580	1.594	0.744	-0.135
385	0.002	-0.002	0.011	585	1.859	0.583	-0.119
390	0.003	-0.003	0.022	590	2.088	0.425	-0.103
395	0.006	-0.005	0.039	595	2.268	0.279	-0.086
400	0.011	-0.010	0.073	600	2.374	0.154	-0.072
405	0.018	-0.017	0.119	605	2.413	0.050	-0.058
410	0.033	-0.031	0.224	610	2.370	-0.028	-0.047
415	0.058	-0.056	0.402	615	2.259	-0.082	-0.037
420	0.099	-0.096	0.698	620	2.086	-0.113	-0.029
425	0.154	-0.151	1.124	625	1.854	-0.126	-0.022
430	0.194	-0.196	1.498	630	1.598	-0.125	-0.017
435	0.211	-0.219	1.754	635	1.357	-0.118	-0.013
440	0.204	-0.322	1.886	640	1.128	-0.106	-0.010
445	0.177	-0.207	1.923	645	0.913	-0.090	-0.007
450	0.134	-0.181	1.909	650	0.719	-0.074	-0.005
455	0.080	-0.146	1.875	655	0.556	-0.059	-0.004
460	0.014	-0.100	1.791	660	0.420	-0.045	-0.003
465	-0.060	-0.041	1.634	665	0.309	-0.034	-0.002
470	-0.141	0.035	1.369	670	0.223	-0.025	-0.001
475	-0.217	0.117	1.098	675	0.162	-0.018	-0.001
480	-0.287	0.202	0.844	680	0.120	-0.013	-0.001
485	-0.351	0.287	0.624	685	0.084	-0.010	-0.000
490	-0.413	0.378	0.452	690	0.058	-0.007	-0.000
495	-0.483	0.485	0.320	695	0.041	-0.005	-0.000
500	-0.564	0.612	0.217	700	0.029	-0.003	-0.000
505	-0.661	0.770	0.134	705	0.021	-0.002	-0.000
510	-0.748	0.941	0.055	710	0.015	-0.002	-0.000
515	-0.811	1.117	-0.018	715	0.010	-0.001	-0.000
520	-0.833	1-274	-0.075	720	0.007	-0.001	-0.000
525	-0.797	1:384	-0.113	725	0.005	-0.001	-0.000
530	-0.714	1.458	-0.141	730	0.004	-0.000	-0.000
535	-0.597	1.499	-0.162	735	0.003	-0.000	-0.000
540	-0.449	1.509	-0.177	740	0.002	-0.000	0.000
545	-0.271	1.491	-0.186	745	0.001	-0.000	-0.000
550	-0.063	1.447	-0.189	750	0.001	-0.000	-0.000
555	0.172	1.380	-0.188	755	0.000	-0.000	-0.000
560	0.433	1.290	-0.183	760	0.000	-0.000	-0.000
565	0.713	1.178	-0.175	765	0.000	-0.000	0.000
570	1.007	1.047	-0.164	770	0.000	-0.000	0.000
575	1.304	0.901	-0.150				

6.6. A possible method of evaluating colour fidelity

The values that have been calculated above may serve to place the camera under test in one of a series of classes established according to values obtained for a large number of cameras which have been statistically analysed. Such a classification has been proposed [16] on the basis of results obtained following the colour fidelity measurement campaign conducted by EBU Sub-group G4 in 1980. These results cover 63 studio cameras examined, in common specified experimental conditions, with sets of CIE samples (1 to 14, except 12) which had been manufactured in a single batch by one laboratory (BAM, Berlin), so as to reduce the disparities in their characteristics.

The distribution of the cameras covers four classes, as a function of their mean colour-difference values for the desaturated samples, on the one hand, and for all the samples, on the other.

A further measurement campaign was conducted in 1982 with, in particular, a common set of samples throughout; the results are in the process of being analysed. It is expected that these additional results will lead to some refinement of the method.

CHAPTER 7
Calculation procedure: special cases

7.1. Calculations for a W, R, B camera

All the calculations explained so far concern R, G, B cameras. In a W, R, B camera, the W channel has a slightly wider frequency response than that used in the G channel. However, the main difference is that at the output of the matrix there is a separate luminance signal in addition to the Rm, Gm, Bm signals. The Wm signal is derived from the W channel of the camera, to which a part of the R signal is added. In the coder, the luminance signal Y is as usual formed from appropriate quantities of Rm, Gm, Bm, although it is not transmitted; it is the Wm. signal which is transmitted and which is used in the decoder. This causes an error in the decoded signal, commonly referred to as the "AL" error.

The signals that are measured or calculated (in the case of the spectrophotometric method) after the electronic matrix are Rm, Gm, Bm and Wm. In a system with an overall gamma of 1, the gamma correction in the camera (g_c) must theoretically be the inverse of that of the picture tube in the receiver ($g_d = 1/g_c$). The signals after coding and decoding become:

$$R_{\Delta L} = \left[R_m^{g_c} - \left(0.299R_m^{g_c} + 0.587G_m^{g_c} + 0.114B_m^{g_c}\right) + W_m^{g_c}\right]^{g_d}$$

$$G_{\Delta L} = \left[G_m^{g_c} - \left(0.299R_m^{g_c} + 0.587G_m^{g_c} + 0.114B_m^{g_c}\right) + W_m^{g_c}\right]^{g_d}$$

$$B_{\Delta L} = \left[B_m^{g_c} - \left(0.299R_m^{g_c} + 0.587G_m^{g_c} + 0.114B_m^{g_c}\right) + W_m^{g_c}\right]^{g_d}$$

$R_{\Delta L}$, $G_{\Delta L}$, $B_{\Delta L}$ are the signals effectively used by the display tube in the receiver. Their values, therefore, are to be used with the transformation matrix $T\left(R_n, G_n, B_n \rightarrow X_n, Y_n, Z_n\right)$. After that, the calculations continue as in Section 6.2.

7.2. Accounting for the gamma correction

So far it has been assumed that the system under test has been perfectly linear. In this hypothetical system, the camera tubes have a linear characteristic and the characteristic of the gamma corrector (g_c) is exactly the inverse of that of the display tube (g_d). The unity gamma system can be considered as comprising a camera with g_c = 0.45 and a monitor with g_d = 2.22. If the camera also had an ideal spectral response (i.e., if, for any colour, the output signal characteristics were equal to the tristimulus values of the original colour in the colour reference system used in the display device), the colour reproduced by such a monitor could be made to correspond exactly, in metameric terms, with the original colour, when observed with a relatively light daylight surround as used in the CIE matching experiments. The unity gamma system may also be considered as being composed of a unity gamma camera and a unity gamma monitor. It is this latter concept which is implemented in the measurement methods described in the foregoing chapters.

The condition g_c = 1 will, in practice, be sufficient to obtain linear operation of the camera if the non linearity of the camera tubes is small enough to be neglected. However, it must not be forgotten that the gamma correctors cannot, in practice, obey a simple logarithmic law over the entire range of input levels as such a law would imply infinite gain close to the black. The maximum gain is limited to a compromise (mainly governed by noise) which is generally between 3 and 10. Its effect on the measured colour difference may be important and should therefore not be ignored. (For example, ΔE^* may be as high as 25 for a maximum gain of 3, whilst being equal to 1.3 for a maximum gain of 7).

If the effects of gamma are to be investigated, the following procedures should be adopted:

For the real samples method

Measurements can be made with the gamma corrector in circuit (0.45) and the results raised to a gamma of 2.22 to give the corresponding signal values for a linear system. A check should be made to ensure that the gamma actually implemented does correspond with the indicated law. The camera should be adjusted very carefully on a calibrated grey scale and the channel alignment should be checked very attentively. It may be helpful to use a differential amplifier for this purpose.

For the spectrophotometric method

The effect of gamma correction can be investigated by separately measuring the transfer characteristic and applying correction to the calculated R, G, B values using a "look up" table.

This technique can also be used with the real samples method, for example, to investigate the effect of changing the transfer characteristic of the camera.

Cameras with non-linear matrix correction (matrix after gamma correction) can be investigated in the following way:

a) measurements are carried out with the matrix off and with unity gamma;

b) the gamma correction of the linear R, G, B signals (measured or calculated) is then computed as above;

c) the matrix calculation is then applied

$$\begin{vmatrix} R' \\ G' \\ B' \end{vmatrix} = M \cdot \begin{vmatrix} R \\ G \\ B \end{vmatrix}$$

d) thereafter, the calculation proceeds as normal

APPENDIX 1
Reference white, surfaces

The standard white reference in the CIE system, for reflectance measurements, is a perfectly diffusing and perfectly reflecting surface with a spectral reflectance equal to 1 (or 100%) over the whole visible region. As the best practical approximation to this, the CIE has recommended the surface of a plaque of pressed barium sulphate ($BaSO_4$) powder.

The same working standard is to be used for television colorimetric measurements. The barium sulphate surface represents 100% reflectance in all real sample measurements. It is the reference for camera white balance before measurement and for the spectral radiance factors of the original samples. However, in television a 60% white is commonly used for routine white-balancing. The influence on the results of colour measurements and computations of the use of a 100% reference instead of a 60% reference is only a scaling factor for the colour difference. The latter will always be greater for 60% white.

The barium sulphate reference has a very sensitive surface, however, which may be easily contaminated by dust, etc. Cleaning by brushing is difficult and may cause significant changes to the reflectance properties. For use with the real samples method, a white reference with a more robust and preferably cleanable surface would therefore be more practical. The reflectance of such a surface should preferably be more than 80%.

Highly reflective materials exist which can be used as working references. If it is wished to use them for television colorimetric measurements, the reflectance properties relative to $BaSO_4$ must be known. If this information is not supplied, it must be determined by measurements relative to a $BaSO_4$ surface.

Representative reflectance data for some practical white surfaces are given in Table 1.1.

The implementation procedure for such references is the following. The camera is first white-balanced and the peak signal adjusted to 700 mV in each channel for the $BaS0_4$ surface. Then the practical white reference is substituted and the three channel signals R, G, B are measured. The practical white reference can now be used for white balancing and adjusting the peak signal to 700 mV. The measured channel signals for each sample must then be corrected by multiplying them by the respective correction factors: R/700, G/700, B/700. The results will then refer to the $BaSO_4$ reference.

Table 1.1. - Spectral radiance factors (%) of some reference white samples

l (nm)	BaSO4 Abs. radiance	Opal glass	NPL tile	Color Checker white	BAM No. 17
380	99.7	87.2	80.8	12.5	10.8
390	99.9	89.3	84.4	21.0	17.3
400	100.0	90.0	86.8	31.5	35.0
410		92.0	87.7	65.8	60.7
420	100.1	92.5	88.2	84.4	72.2
430		92.9	88.6	87.9	74.1
440	100.2	93.2	88.8	88.2	74.5
450		93.6	89.1	88.7	74.7
460	100.3	94.2	89.6	89.0	74.8
470		94.5	89.9	89.4	75.1
480	100.4	94.6	90.0	88.9	75.2
490		94.9	90.2	89.3	75.6
500	100.4	95.1	90.4	89.2	75.9
510		95.2	90.4	88.9	76.0
520	100.4	95.2	90.7	89.4	76.1
530		95.2	90.8	89.3	76.2
540	100.4	95.2	90.8	89.1	76.0
550		95.0	90.0	88.5	76.0
560	100.5	94.8	90.9	89.0	76.4
570		94.5	90.8	89.4	76.4
580	100.5	94.3	90.7	89.7	76.4
590		94.1	90.7	89.9	76.4
600	100.5	93.9	90.9	89.5	76.4
610		93.7	91.0	89.7	76.1
620	100.5	93.7	90.9	89.0	76.0
630		93.6	91.0	88.8	75.8
640	100.5	93.6	91.1	89.2	75.8
650		93.5	91.0	89.1	75.8
660	100.6	93.5	91.0	89.6	75.8
670		93.6	91.3	89.7	75.7
680	100.6	93.6	91.4	89.1	75.6
690		93.5	91.3	89.2	75.6
700	100.6	93.4	91.4	89.0	75.6
710		93.4	91.5	89.1	75.4
720	100.6	93.3	91.5	89.0	75.4
730		93.2	91.5	89.3	75.4
740	100.6	93.1	91.3	88.8	75.1

The correction factors should hold with sufficient accuracy for cameras of the same type, although for cameras where significantly different response characteristics are expected, it will be necessary to make separate measurements of the correction factors. This is, of course, a complication which is avoided if the measurements refer directly to the $BaSO_4$ surface.

Calibrated white tiles and opal glass references can be obtained from the National Physical Laboratory, Teddington, UK.

BaSO4 powders that can be used for reference whites can be obtained from: Kodak Laboratory and Speciality Chemicals, Eastman Kodak Company, Rochester, New York 14650. In Europe, such powders are manufactured by E. Merck, Darmstadt, West Germany. They can be obtained with spectral control data by Physicalische Technische Bundesanstalt, West Germany, through Carl Zeiss, D-7082 Oberkochen, West Germany. The latter company also supplies a device for pressing the plaques.

APPENDIX 2
Light sources for samples illumination

For the reasons indicated in the text, the colour temperature of the lighting to be used in the measuring installation should be close to that of studio lighting. In order to ensure stable operating conditions and longer lamp life, it is recommended that a colour temperature of the order of 3100 K be used. It should not be forgotten, however, that the radiation effectively produced by an incandescent lamp is not exactly similar to the black body radiation which serves to qualify the colour temperature. Its chromaticity cannot, therefore, be correctly defined by the latter concept. In leading national standards laboratories, the uncertainties quoted may be less than 10 K. However, for calibrations at industrial laboratories, greater uncertainties must be expected. It would therefore appear inappropriate to set a tolerance of, for example, 50 K. Furthermore, for a given voltage, the lamps currently used in television studios show a non-negligible spread of colour temperature values [17]. To limit this spread in the measuring installation, it may be helpful to use calibrated lamps.

It seems reasonable to adopt a tolerance of ± 100 K. Calculations have been made to verify the effect of this tolerance on the colour difference. In effect, a variation in the colour temperature leads to a differential variation in the luminous fluxes analysed in the R, G and B channels, this resulting in variations in the camera balance on the reference white. The response of a given camera to some CIE samples has been measured for various colour temperatures around 310O.K, the camera being re-balanced before the measurements were taken at each colour temperature. The results obtained for the average colour differences were as follows.

T	**3000 K**	**3100 K**	**3200 K**
ΔE^*_a (1-17)	6.32	6.47	6.56

It can be seen that the effect of this tolerance on the colour temperature is very small indeed.

Even if the precision in the implementation of the colour temperature may be only ± 100 K, the chosen colour temperature should be kept constant and this implies high stability in the supply voltage. Experience gained In spectroradiometry measurements leads to similar conclusions, as It shows that a specification of 0.1% is necessary for the stability of the power supply.

Measurement of lamp voltage has the advantage that it is nearly twice as sensitive as current measurement. However, it is also sensitive to bad lamp contacts. In practice it is therefore probably better to measure the current.

To obtain the required accuracy in the measurement of colour temperature stability, the use is recommended of a current measuring instrument giving a readout with an accuracy of at least 0.2%. With DC operation it may be advantageous to switch the supply polarity regularly. AC operation can also be used, provided that the required regulation accuracy can be achieved. In any event, lamps should be operated with the type of current used in their calibration.

The colour temperature will decrease with burning time, but the rate of decrease will vary with the type of lamp. Exact data are difficult to find but, from figures in the available literature, the following orders of magnitude seem reasonable for a decrease of 100 K (from a calibrated temperature of 3000 K):

400 hours for mains-voltage gas-filled projection type lamps 600 hours for low-voltage (thick filament) halogen lamps

The use of low-voltage halogen lamps is therefore recommended.

APPENDIX 3
Colour samples

The selection of the colour samples is one of the more delicate problems to be resolved in devising an objective method for the evaluation of colour rendering. The CIE has recommended fourteen samples, defined by their Munsell notations, for use in evaluations of the colour rendering of light sources. Much use has been made, in television colorimetry, of samples which are metameric matches to certain of the CIE samples. This is the case for the samples indicated at the beginning of Table 3.1. These samples are manufactured and calibrated in sets of 13 coloured samples by the Bundesanstalt für Materialprüfung, Unter den Eichen 87, D-1000, Berlin 45, West Germany. The calibration data are provided in the form of a table. These are matt samples corresponding to CIE colours 1 to 11, 13 and 14 (colour No. 12, which falls outside the zone defined by the EBU phosphors, is of no use in television). We have not shown the characteristics of sample No. 11 in Table 3.1 because it gives virtually no more information than sample No. 4 which comes just to its right In the u, v diagram.

The table mentions some other samples which have been made for special studies. EBU samples 21, 22 and 25 are part of a collection (EBU 21 to 26) which has been defined by the EBU for the measurement of the colour rendering of film-scanners.

Table 3.1 is only a preliminary suggestion as regards the compilation of a collection. Samples Nos. 14, 17, 21, 24, 25, 27 and 28 are intended to check for effects of non-linearities in the camera. In the case of a linear system, the twenty-one other samples may be sufficient.

Until such time as EBU Sub-group G4 has defined an optimal set of samples, and until the corresponding sets of samples are manufactured, it may be helpful to use the sets already available on the market.

An important collection is the Macbeth Colour Checker chart, containing 18 coloured and six neutral samples. Some spectral and colorimetric data for these are given in [181. The light skin tone and the neutrals in Table 3.1 are from this collection. It is made by Munsell Color, 2441 North Calvert Street, Baltimore, Maryland 21218, USA. Spectrophotometric curves can be supplied.

Table 3.1. Colour samples suitable for me An television

No.	Samples	Munsell notation	Co-ordinates					
			u'	v'	u*	v*	Y	L*
1	CIE 1	7.5 R 6/4	0.239	0.486	32.6	13.8	28.8	60.6
2	CIE 2	5 Y 6/4	0.216	0.512	14.7	35.1	29.9	61.6
3	CIE 3	5 GY 6/8	0.186	0.539	-9.7	56.1	29.6	61.3
4	CIE 4	2.5 G 6/6	0.155	0.505	-34.2	28.9	29.6	61.3
5	CIE 5	10 BG 614	0.164	0.457	-27.8	-9.0	31.6	63.0
6	CIE 6	5 PB 6/8	0.172	0.418	-20.4	-39.6	29.3	61.0
7	CIE 7	2.5 P 618	0.210	0.421	9.6	-37.3	28.9	60.7
8	CIE 8	10 P 618	0.236	0.436	31.1	-26.1	31.2	62.7
9	CIE 10	5 Y 8/10	0.224	0.546	27.0	81.4	56.9	80.1
10	CIE 13	5 YR 8/4	0.230	0.495	32.5	27.5	54.8	78.9
11	CIE 14	5 GY 414	0.186	0.515	-6.8	27.0	14.2	44.5
12	Color Checker light skin		0.234	0.492	31.7	20.3	36.4	66.8
13	EBU 21 (TDF 7)	5 R 5/10 red pair	0.315	0.492	78.8	16.2	20.0	51.8
14		5 R 3/6	0.310	0.485	45.0	6.8	6.6	30.9
15	EBU 22	5 YR 7/10	0.275	0.525	70.7	52.1	41.1	70.3
16	TDF 1	5 Y 6/8	0.227	0.541	23.3	58.6	30.0	61.7
17	TDF 2	10 GY 7/10 green	0.153	0.533	-42.2	61.0	43.9	72.2
18		10 GY 5/8	0.151	0.533	-31.5	43.6	19.8	51.6
19	TDF 3	10 BG 6/8	0.136	0.442	-49.7	-20.8	30.0	61.7
20		7.5 PB 5/12 blue pair	0.176	0.348	-14.8	-80.5	19.8	51.6
21	EBU 25	7.5 PB 3110	0.176	0.342	-8.7	-49.8	6.5	30.4
22	TDF 5	5 P 5110	0.222	0.394	16.1	-49.6	19.8	51.6
23	TDF 6	5 RP 5/12	0.300	0.442	68.4	-17.4	19.8	51.6
24	Color Checker (59%)	neutral	0.198	0.467			59.0	
25	Color Checker (36%)	neutral	0.198	0.467			36.0	
26	Color Checker (20%)	neutral	0.198	0.467			19.8	
27	Color Checker (9%)	neutral	0.198	0.467			9.0	
28	Color Checker (3%)	neutral	0.198	0.467			3.1	

The Munsell colour collection consists of a very large number of samples ordered in approximately equal visual steps of hue, value and chroma. Samples from this collection are much used in colorimetry, and for both the above collections equivalent colours exist in Munsell system. Samples and spectrophotometric curves are available from the same address as the Color Checker chart.

A set of nine coloured and three neutral ceramic tiles, can be obtained very accurately calibrated from the National Physical Laboratory, Teddington, UK. These are stable and are therefore well suited as references for checking colorimetric equipment. Representative values are shown in Table 3.2.

Whichever collection is chosen, the range of saturated blue to purple colours is rather limited and therefore it is difficult to find suitable saturated test samples for this part of the EBU RGB triangle.

Table 3.2. Co-ordinates of NPL ceramic tiles (illuminant D_{65}, geometry: 0/45)

Colour	u'	v'	Y
Maroon	0.349	0.486	2.1
Pink	0.238	0.476	41.3
Brown	0.295	0.528	16.2
Yellow	0.221	0.545	62.2
Light green	0.179	0.494	30.9
Dark green	0.161	0.531	6.1
Greenish blue	0.148	0.455	7.3
Medium blue	0.171	0.414	12.1
Dark blue	0.195	0.262	1.2
Dark grey	0.194	0.460	5.0
Medium grey	0.193	0.467	26.3
Light grey	0.197	0.472	60.0

Table 3.3.- Spectral radiance factor $b(l)$ of BAM Samples Nos. 1 to 8

l (nm)	1	2	3	4	5	6	7	8
380	0.214	0.116	0.063	0.134	0.232	0.313	0.354	0.367
390	0.219	0.121	0.070	0.151	0.262	0.392	0.428	0.439
400	0.219	0.123	0.074	0.161	0.285	0.466	0.486	0.487
410	0.217	0.123	0.074	0.162	0.297	0.511	0.510	0.504
420	0.215	0.123	0.073	0.161	0.307	0.529	0.515	0.501
430	0.215	0.126	0.072	0.163	0.318	0.544	0.519	0.487
440	0.217	0.131	0.072	0.169	0.334	0.559	0.519	0.464
450	0.217	0.137	0.074	0.181	0.356	0.568	0.511	0.435
460	0.217	0.142	0.077	0.198	0.386	0.567	0.495	0.411
470	0.217	0.147	0.083	0.216	0.412	0.557	0.470	0.381
480	0.216	0.156	0.095	0.244	0.419	0.538	0.435	0.347
490	0.213	0.176	0.125	0.299	0.424	0.507	0.393	0.326
500	0.214	0.205	0.191	0.378	0.425	0.471	0.350	0.309
510	0.218	0.230	0.274	0.428	0.405	0.433	0.310	0.281
520	0.220	0.250	0.317	0.429	0.380	0.392	0.277	0.254
530	0.220	0.267	0.319	0.410	0.370	0.357	0.261	0.248
540	0.227	0.284	0.330	0.383	0.361	0.328	0.254	0.252
550	0.247	0.298	0.375	0.347	0.328	0.293	0.247	0.242
560	0.274	0.310	0.410	0.308	0.296	0.257	0.239	0.233
570	0.306	0.321	0.392	0.272	0.282	0.232	0.254	0.253
580	0.343	0.330	0.350	0.245	0.275	0.222	0.284	0.322
590	0.379	0.336	0.303	0.218	0.249	0.220	0.315	0.409
600	0.406	0.339	0.261	0.190	0.211	0.217	0.332	0.464
610	0.422	0.339	0.230	0.170	0.184	0.215	0.330	0.475
620	0.433	0.339	0.216	0.161	0.170	0.219	0.324	0.468
630	0.438	0.338	0.211	0.159	0.165	0.231	0.334	0.476
640	0.443	0.338	0.209	0.160	0.164	0.251	0.370	0.512
650	0.448	0.337	0.210	0.163	0.166	0.272	0.417	0.559
660	0.452	0.338	0.217	0.172	0.174	0.287	0.459	0.603
670	0.461	0.341	0.235	0.186	0.191	0.291	0.487	0.638
680	0.469	0.343	0.255	0.202	0.213	0.284	0.494	0.657
690	0.479	0.346	0.274	0.216	0.233	0.277	0.495	0.669
700	0.488	0.350	0.288	0.227	0.247	0.278	0.501	0.678
710	0.498	0.354	0.293	0.232	0.252	0.290	0.517	0.690
720	0.508	0.358	0.292	0.234	0.250	0.310	0.543	0.705
730	0.508	0.358	0.292	0.234	0.250	0.310	0.545	0.705
740	0.508	0.358	0.292	0.234	0.250	0.310	0.545	0.705
750	0.508	0.358	0.292	0.234	0.250	0.310	0.545	0.705
760	0.508	0.358	0.292	0.234	0.250	0.310	0.545	0.705

APPENDIX 4
An illumination and sample-presentation arrangement for the real samples method

Apparatus has been designed by Mr. Hisdal of NRK to ensure uniform presentation of all the samples in a collection. Fig. 4.1 shows a photograph of the arrangement (seen from above). It consists of a Kodak carousel projector (1) (from which the optics and mains transformer have been removed), the slide magazine (2) in which the reflective samples are stored (protected from dust and from being soiled by handling), two cylindrical lamp houses (3), the lamps illuminating the sample at an angle of 45° from each side and a holder (4) for the $BaSO_4$ white reference plaque (or calibrated ceramic tile). The calibrated lamps (100W, 12V halogen) are mounted on slides (5) so that their distance from the sample surface can be adjusted to give even combined illumination over the sample surface. A flap (6) can be put over the arrangement during measurement to shield against extraneous light.

The front (7), which is covered with black velvet, is protected by a lid when the equipment is not in use. In the centre of the lid and front plate is a hole which, on the lid, is surrounded by a white ring; this is shown in Fig. 4.2. During measurement, the lid is lifted up so that the black-velvet-covered front surface is seen by the camera, as shown in the lower part of the figure.

The carousel projector (1), and the holder (4) for the white reference or ceramic tile, are mounted on a common base-plate which is also mounted on roller-bearing slides. The projector and holder can therefore be positioned so that either the sample surface is illuminated, as shown in Fig. 4.3.A, or the white surface in the holder is illuminated, as shown in Fig. 4.3.B.

In addition to the parts mentioned, there are filter holders in each light path in which neutral filters, or filters giving an approximation to daylight, can be inserted. A small electric fan is mounted under each lamp. A neutral filter can also be mounted over stop S1 (Fig. 4.3) for use in connection with measurements of the camera transfer characteristic by means of the superposition method.

Before starting to take measurements, the camera is mounted normal to the sample surface in the following way: with room illumination on, the camera is focussed on the white ring on the lid over the front surface. The black area around stop S1 can then be seen inside the ring and, inside this, is the illuminated ample surface. The camera position (or the measurement apparatus) is then adjusted until the hole of S1 is centred within the white ring (or the black area around S1 is seen as a black ring of even width within the white ring). In this way, the camera can easily be positioned normal to the sample surface to a higher accuracy than the tolerance of ± 5° required in the CIE method.

Using the projector remote-control unit, the samples can now be presented one after another by an operator seated at the camera and recording the R, G, B signal levels for each sample.

The measurements can be performed at average room illumination levels. The total measurement time is mainly determined by how fast the signal values are written down. If very fast operation is required, the whole operation can of course be automated and the signals fed directly to a computer, programmed to print out the desired ?E * values, or any other desired quantity.

White balance is performed by sliding the $BaSO_4$ reference into position. It is also possible to make white references that can be mounted in the slide magazine and presented in the same way as the colour samples.

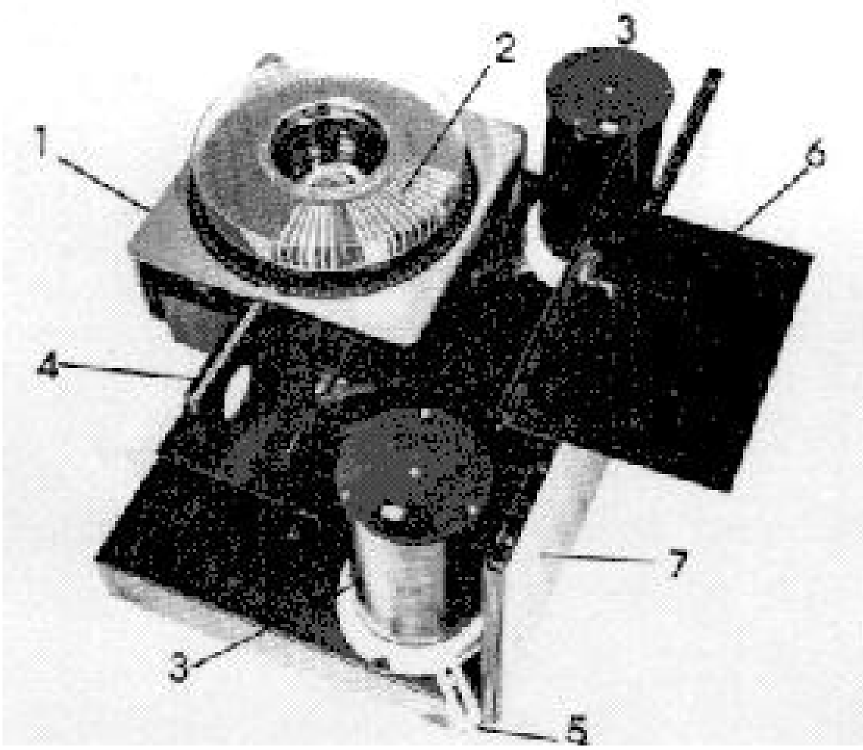


Fig. 4.1.- Overall view of the apparatus used to present the samples

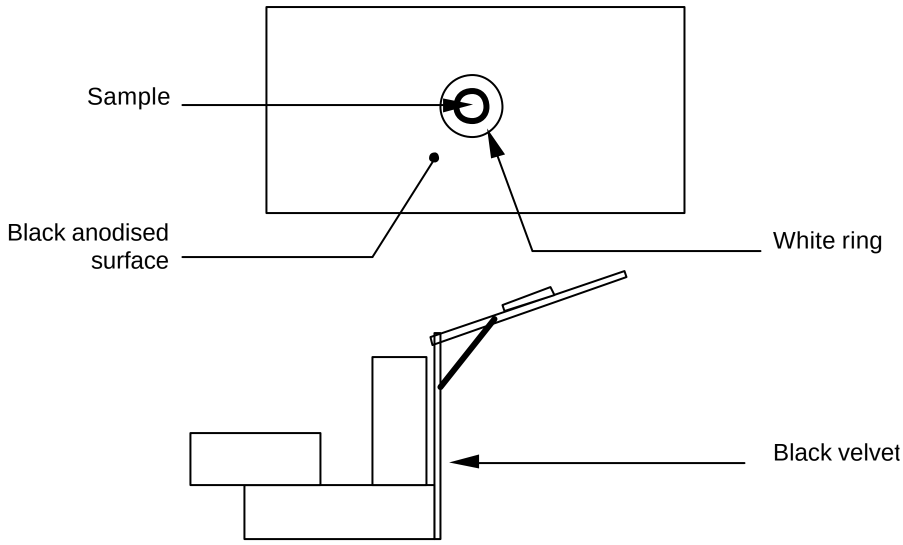
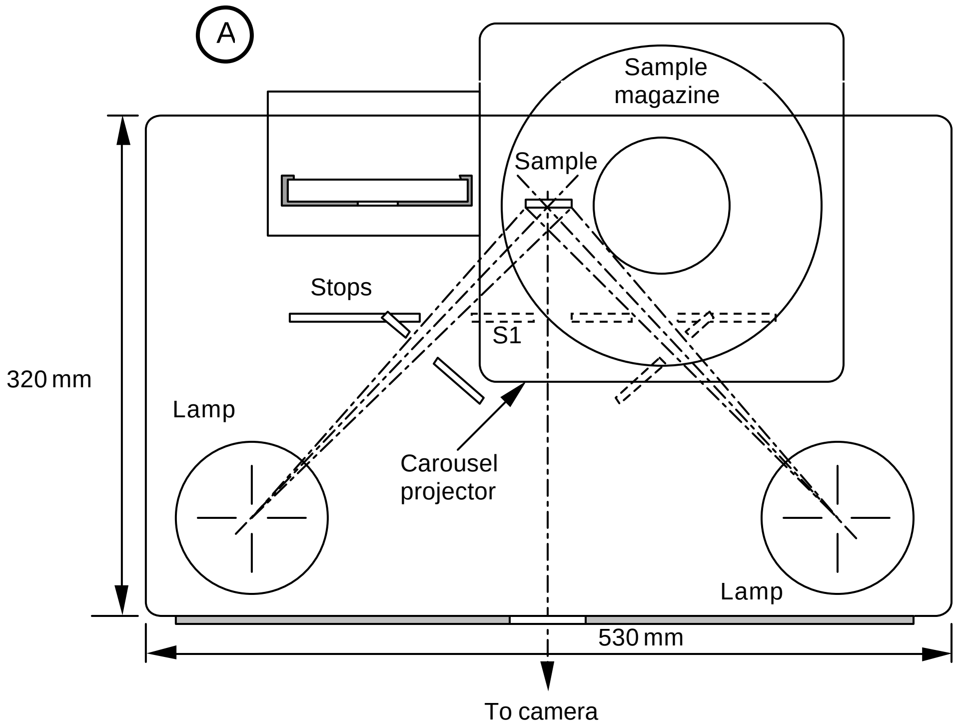


Fig. 4.2, Front and side views of the apparatus



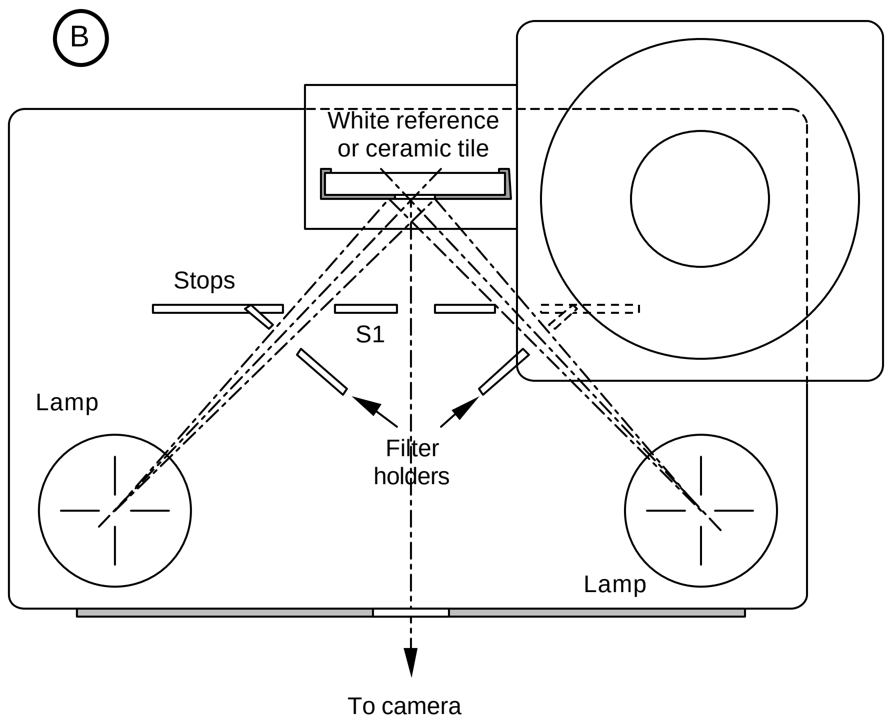


Fig. 4.3: - Plan views of the apparatus used to present the samples

APPENDIX 5
Two other methods for measuring the colour rendering of cameras

1. Spectrophotometric measurements by means of an interference wedge

The interference wedge (Veril filter) is a multi-layer quarter-wave plate the thickness of which varies linearly along the length of the glass support. Its use in spectrophotometric measurements enables (in contrast to the method described in Chapter 4) all monochromatic radiations in the visible spectrum to be juxtaposed simultaneously in the form of vertical bands along the horizontal support scanned by the camera. The spectral response of the camera can then be presented on an oscilloscope or plotted by a suitable recording device [19].

The wedge is mounted behind a light source giving uniform diffuse illumination along the measurement area. The transmitted radiation is therefore a function of both the light source used and the transmission of the wedge. If the measured curves are to be used for computational purposes, the output must therefore be calibrated so that the influence of the light source is known and can be included in the computations. The stability of the light source must be good, as this method has no monitoring cell to verify the individual spectral outputs. Wavelength markings along the wedge can be provided by opaque, or transmitting, illuminated lines or holes in front of the wedge, giving negative or positive spikes in the output signal. Also, a spectral lamp may be used in the illuminating unit behind the wedge, to give peaks at known wavelengths. The spectral bandwidths of interference wedges are about an order of magnitude wider than those quoted for a monochromator (in the case of wedges made by Schott & Gen., Mainz, West Germany).

Prior to measurement, the shading of the camera must be adjusted to give a uniform response over the entire target. Using a video level meter, the area of integration must be of small horizontal width, and the vertical height must be just sufficient to cover the height of the interference wedge. Some idea of the amount of stray light at a particular wavelength may be gained by noting the change in reading when masking the wedge areas on both sides of the narrow vertical area measured by the video level meter. Ambient light must be excluded.

This method is simple and practical as far as equipment is concerned, and should be very well suited for comparative investigations and routine checks.

2. Subjective comparison of reproduced real colours with electronically-generated reference colours

In this method [20] the signals for the original colours of a set of test samples (calculated) can be stored in digital form in a computer memory. These can be reproduced as vertical colour bars on a monitor screen. If the camera views the same real test colours in the form of vertical stripes, these can also be reproduced as vertical bars on the screen. By use of a special-effects mixer and appropriate electronic apparatus it is possible to display both sets of colour bars on the screen simultaneously; one set occupies the upper half and the other set the lower half of the screen. The match between the colours on the same vertical bar can then be evaluated subjectively across a very narrow dividing line. This makes it easy to observe how the reproduced colours are affected by changes in the optical or electronic parts of the transmission chain. The differences can also be studied by means of an oscilloscope and a vectorscope. Possibilities exist for measuring and computing the chromaticity co-ordinates of the colours and therefore also the colour differences. For computation of the stored signal, the phosphor chromaticities of the particular monitor used and the system gamma must be known. The gamma corrector of the camera to be measured must then be adjusted to give the same nominal system gamma. Nonetheless, an examination needs to be made of the colour shifts Introduced by the practical gain limitations of the gamma correctors (see Section 7.2).

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D/1983/0299/209

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