



NPL Spectrophotometry and Colorimetry Club

THE COLORIMETRY OF VISUAL DISPLAYS



Club working party on visual displays

September 1995

The colorimetry of visual displays

Terms of Reference

"To write and publish a report on the following aspects of the colorimetry of visual displays:

- current and possible future needs of industry for such measurements,**
- instrumental approaches to measurement techniques,**
- measurement procedures, including traceability."**

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ISSN 0309-3050

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Approved on behalf of Chief Executive, NPL,
by Dr J R Gott, Head, Division of Quantum Metrology

Acknowledgements

The Chair of the Working Party is grateful to the following for their valuable contributions to this report:

Keith Bennet	Metax Ltd.
Teresa Goodman	NPL
Geoff Hammond	Bentham Instruments Ltd.
Arthur Jenkins	Philips Research Labs.
Ronnier Luo	University of Derby
Lindsey MacDonald	Crosfield Electronics
David Nettleton	NPL
Keith Oakey	Smiths Industries
Linden Stead	Minolta UK
David Travis	BT Laboratories
Julie Taylor	NPL
John Verrill	NPL

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INTRODUCTION

This report is written by manufacturers and users of both displays and the instruments for their colour measurement. It concentrates on only colorimetric and optical properties of displays. The setting of drive circuitry currents and voltages is beyond the remit of the terms of reference.

The colorimetry of visual displays requires many considerations additional to general practices of colorimetry. This report will concentrate on topics relating to specific displays technologies and detection systems.

Broadly speaking the areas which differentiate the measurement of the colour of displays, from say, the colour of reflecting surfaces are as follows.

- A display often conveys information by emission of light rather than by reflection of incident light. Such display measurements will be traceable to a radiance scale, not a reflectance scale. The radiance scale is not easy to realise locally and in addition, to achieve inter-instrumental agreement, the scale must be related to a master scale such as a National Scale.
- Display images are dynamic. The colour and position of image elements changes continuously. The properties to be measured are the end result of a complex system not a single piece of material. The fact that we have contrived flexible and dynamic control over the content of displays inevitably means that it is susceptible to a wide range of corrupting influences which have to be understood and characterised.
- The various technologies for generating the emitted light give rise to additional measurement hazards in the spectral, spatial and the temporal domain.
- The conditions of the display calibration should, when possible, replicate the conditions of use. An example of this is ambient light which will reduce contrast ratio of a display as it raises the black level.

Clearly most of the recommendations and practices of good colorimetry are relevant to the colorimetry of displays, but displays present their own additional constraints and hazards which are outlined in this report.

1 DISPLAY TECHNOLOGY OVERVIEW

There is a wide range of display technologies. This chapter describes the challenges posed to a colorimetrist as a result of these various technologies.

1.1 CATHODE RAY TUBES

1.1.1 Colour CRT technology

Colour CRT displays are dominated by the "Shadow-Mask" CRT technology. Other technologies such as the penetration phosphor CRT and the Beam-Index CRT have aroused brief interest but have not found widespread application. The only other technology in significant use is the 3 CRT projection system for application when a large picture is needed. This has found a niche in the U.S. domestic television market.

The basic principle of the Shadow-Mask CRT is very simple. Three electron-guns inclined at a small angle to each other are aimed at the same point on the screen.

About 10 mm behind the screen is a perforated metal foil (the Shadow-Mask) having a fine regular pattern of holes. The guns are mutually inclined in order that any one mask hole will give 3 displaced shadows at the screen. If 3 different phosphor types are placed at the 3 shadow positions then any one gun can land electrons at only one phosphor type. If this shadow action can be maintained as the 3 beams are swept together over the screen then modulation of the 3 electron guns will give independent control of light emission from the 3 phosphor types.

This is no trivial task when we consider that mask-shadow to phosphor patch registration has to be maintained within a few tens of micrometers over screen distances of a few hundred millimetres.

Further information on the design and performance of CRT devices can be found in Morrell (1974).

The Shadow Mask CRT is an additive colour system in which a gamut of colours can be obtained by mixing of red, green and blue primaries, with each primary under independent control.

The colorimetrist needs to be aware of the factors in the total environment of the display which can induce colour-variability leading to non-repeatable measurements or measurements which are not valid for the conditions in which the display is to be used. Some of these factors are outlined in the following sections.

1.1.2 Colour variability

Variability of the resultant colour can be modelled by 3 terms:-

- a) Variation of the chromaticity of the primaries.
- b) Variation in magnitude of the primary emissions.
- c) Cross excitation of primaries. (Beam landing error)

These will be referred to in the following text as type (a), (b) and (c) errors.

1.1.2.1 Colour variability due to shadow-mask misregistration

The shadow-mask action is the main candidate for introducing variability, because of the precise registration needed between mask-hole shadow and phosphor patch. Very small misregistration is accommodated by a guard-band in the design and has no effect on the colour. If the misregistration exceeds the guard-band the emission magnitude starts to reduce (type (b) error). With severe misregistration the magnitude falls further but the shadow starts impinging on the wrong colour patch of phosphor giving type (c) error as well.

Misregistration can arise from:

- Departure from ideal internal geometry during manufacture process, yielding registration differences across the screen.
- Thermal distortion of the shadow-mask due to electron beam loading and environment temperature. The effects of thermal distortion will vary across the screen and will depend on the pattern of the electron beam loading. Some shadow-mask designs incorporate thermal compensators but the compensation can lag in time behind the error.
- Mask movement due to imposed vibration.
- Magnetic fields (even terrestrial fields) can distort the electron beam paths and give rise to misregistration.
- The CRT and/or the drive electronics have fine adjustments for registration. Sometimes these are accessible to the user and provide an opportunity for mis-adjustment.

1.1.2.2 Other sources of colour variability

- *Phosphor contamination*
A patch of say blue phosphor could contain a few particles of red or green phosphor and yield a type (a) error.
- *Secondary emission*
Beam electrons intercepted by the mask will yield some secondary electron emission from the hole edges. These will land on the phosphors in a diffuse manner and tend to excite all phosphors, yielding a type (c) error.
- *Phosphor non-linearity*
There is often a significant degree of non-linearity between phosphor excitation and the resultant light output. Non linearities may be different for the red, green and blue phosphors.
- *Electron gun non-linearity*
There is a highly non-linear relation between drive-voltage and beam-current (typically a 2.5 power law), coupled with time and temperature drift of the point from which drive-voltage is defined. This has to be accommodated by complex electronic design and careful adjustment, particularly for avionic applications where there is a

need to dim the display over a 5000:1 range.

- *Setting of white and black points*
Colour errors will arise if both the white points and black levels are not set according to a well defined procedure.
- *Electron gun interaction*
There may be interaction between the strengths of the three electron beams. For example, the amount of red light emitted for a given digital value may change as the amount of blue and green is varied. This can be checked by displaying a series of colours and comparing the predicted with the measured colours. (Cowan & Rowell 1986)

The results of uniformity measurements performed on a 19" colour CRT are shown in Figure 1.1. There are variations in both x and y chromaticities, and in the luminance Y. The variations are worst towards the edges, there are visible chromatic changes in two areas located left and right of centre. The monitor will have been set up for the best overall uniformity.

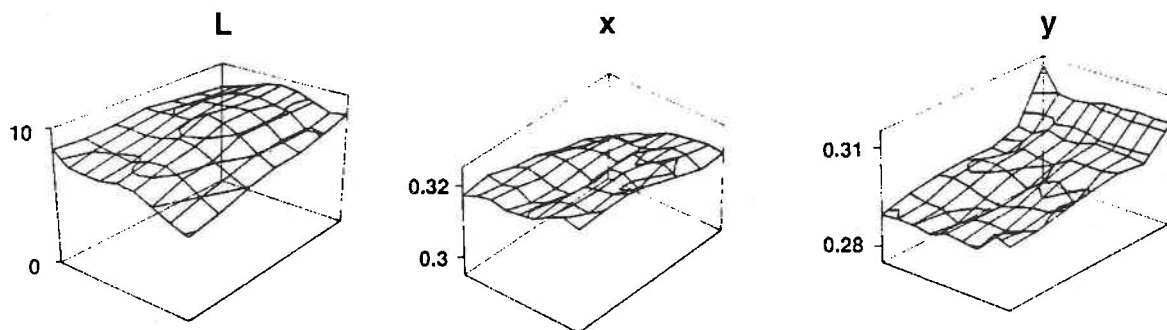


Figure 1.1: Non uniformity in colour and luminance of a CRT

1.1.3 Temporal factors

The luminance and relative radiance from CRTs varies considerably with time. Displays are designed so that changes over the refresh cycle are not visible to the human eye - the refresh rate is maintained just above the frequency at which flicker is perceptible. However this flicker, and other changes will not necessarily be insignificant to a colour measurement device and can affect results.

1.1.3.1 Changes over small periods of time

The light output from any single point on a CRT is in the form of a pulse, typically every 20 ms, taking 3 ms to decay to 100th of the peak value. Most of the energy therefore occurs in a very short part of the display image. The exact decay time will depend on the persistence of the phosphor being used. It is often the case that mixtures of phosphors - for example blue, green, and two reds, will be used at the same time - and all these will have different persistence times. Therefore the colour at any point will vary considerably over a single refresh frame.

1.1.3.2 Changes over medium periods of time

The alignment of the shadow mask will change as it expands with heating following switch on. This will result in a change in chromaticity with time. This, along with other factors relating to the functioning of the device means that it is unwise to begin accurate measurements of colours on a CRT until the system has had time to 'warm up'. The change in spectral power distribution of a white at medium luminance over 100 minutes following turn on is shown in Figure 1.2. Note how the relative heights of the peaks change - this will result in measurable colour changes.

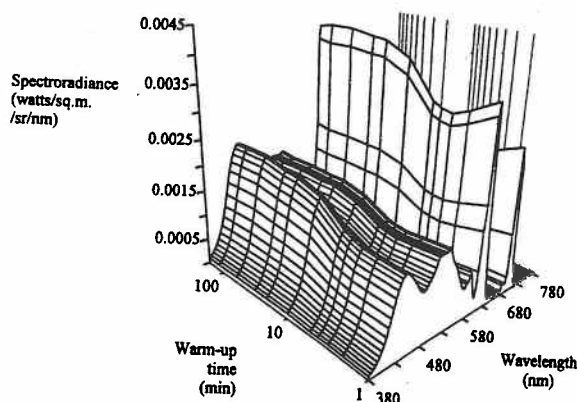


Figure 1.2: Change of spd of CRT following switch on.

1.1.3.3 Changes over longer periods of time

The efficacy of phosphors diminishes with time as they age. In a full colour system, the different phosphors will age differentially causing an overall colour shift.

1.1.4 Spectral factors

As shown in Figure 1.2, the spectral power distribution of a typical phosphor set is complex. It contains sharp peaks in the red. Clearly the spectral resolution of the colour measurement equipment will have a bearing on the quality of the result.

1.1.5 Ambient light

Measurement of light emitted from a CRT will be significantly affected by ambient light - the specular reflection off the surface will cause glare and the diffuse reflectance reduce contrast. If the evaluation is to represent a normal working condition then the measurements must be made within the normal working lighting condition. Alternatively, if a 'standard dark lab condition' is to be used, light may still be present originating from either the display reflected off the walls, or the measurement apparatus.

Ambient light can be assessed by placing a small white opaque reflector directly in front of the display, with the display set to a typical luminance, and measuring the light level on the reflector.

1.1.6 Coatings and shields

Coatings and shields can be mounted to the front of CRTS to reduce effects of visual glare, these should be in place when performing measurements.

1.2 LIGHT EMITTING DIODE (LED) DISPLAYS

The use of LEDs in large area displays has been attempted but found little application because of the thermal management and fabrication cost issues. However LEDs have been used in small area alpha-numeric displays in the form of 7 x 5 dot matrix and dedicated pseudo-analogue displays.

1.2.1 Temporal properties

The constant-current drivers for the LED elements are usually multiplexed in time, yielding pulsed light output with up to 20:1 peak : mean ratio.

Pulse width modulation is sometimes used to extend the number of grey levels. This can further increase the peak/mean ratio.

The refresh rate can be faster than is usual for CRTs since LED displays are not usually tied to any raster-scanning format.

1.2.2 Spectral properties

For LEDs with narrow spectral emission, the spectral resolution of the measuring instrument may affect results.

The emission wavelength and luminous efficiency are both temperature dependent so there can be variability due to both the environmental temperature and to device power dissipation.

1.2.3 Spatial properties

- a) LED matrix arrays tend to use a relatively coarse pixel structure, ie at normal viewing distance the characters can be perceived to be composed from dots.

If there is a visible dot structure, it may be necessary to consider whether area-averaged luminance is the proper parameter for predicting visual performance. This may lead to a need to measure area average luminance rather than dot luminous intensity.

- b) The individual LED elements of an array can exhibit large element to element variability in luminous efficiency, up to 2:1 variation depending on the batch control strategy of the array manufacture.
- c) The polar distribution of light emitted from an LED can exhibit complex patterns and therefore a strong angle of view dependence as shown in Figure 1.3.

In addition a significant fraction of the emitted light comes from the chip side-faces - what happens to this emission depends on the detail design of the array structure.

- d) The reflection of ambient illumination will limit the visual performance attainable so reflectance properties need to be measured.

Many items contribute to the reflectance including:-

- Specular reflectance from chip faces
- Specular reflectance from bond-wires
- Diffuse and specular reflectance from the substrate and substrate metallisation.

All of these factors will be modified by potting or conformal coating, and by the output window material. Thus it becomes important to define and maintain the appropriate geometry for reflectance measurements.

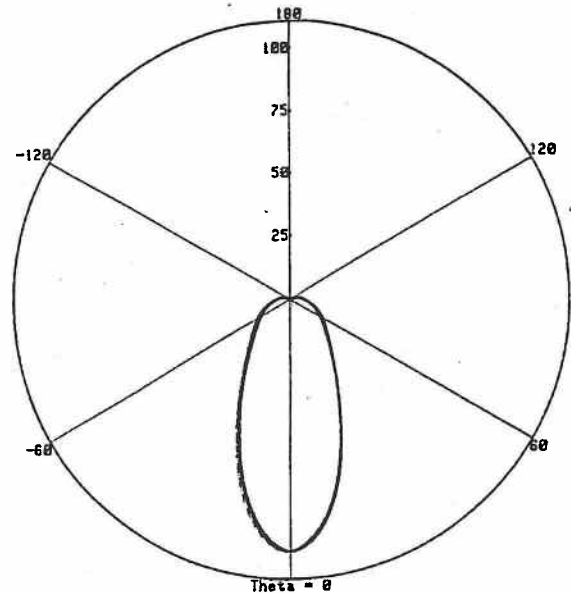


Figure 1.3: Spatial variation - polar plot- for LED

1.3 ACTIVE MATRIX LIQUID CRYSTAL DISPLAYS FOR DIRECT VIEWING APPLICATIONS

1.3.1 Direct view application LCDs

The construction of a colour active matrix liquid crystal cell is shown in Figure 1.4. The liquid crystal material is held between two glass plates which are typically about 1 mm thick. The thickness of the liquid crystal is about 5 micrometres. The lower plate carries a pattern of electrodes for each picture element or pixel. These are made of a transparent conducting layer of indium tin oxide (ITO). In the corner of each pixel is the electronic switch that connects the pixel electrode to the row bus bars. The electronic switch can be either a thin film transistor (TFT), a diode or a metal-insulator-metal (MIM) device.

The top plate carries the column electrodes made of ITO, and the mosaic colour filter which brings colour to the display. Besides having the required spectral characteristics this filter element should not scatter light or contaminate the liquid crystal material and be compatible with the cell making process. The gap between the elements is filled with an

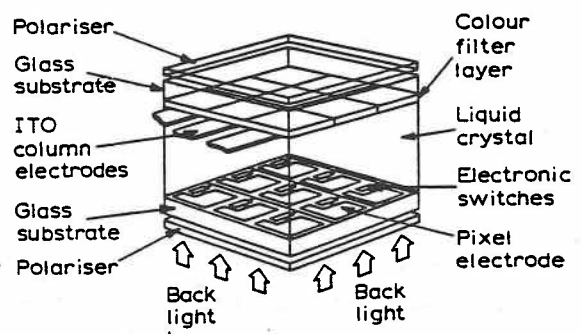


Figure 1.4: Construction of an active matrix colour LCD

absorbing black material. This will cut out un-modulated light between the pixels and mask the row and column structures.

Figure 1.6 illustrates thin film diode addressing. The electrode layout would be different for TFTs which are three terminal devices, having the row and column electrodes on the same plate.

The inside surface of both plates is coated with a thin layer of a polymer, not shown, which is rubbed to provide an alignment layer for the liquid crystal. The cell is constructed so that these alignment layers are at right angles. When the cell is filled, the liquid crystal molecules take up an orientation that is parallel to the alignment layers and also nearly parallel to the plane of the windows. This means that when no electric field is applied the molecules take up a helical structure, as shown in Figure 1.5.

If the cell is illuminated with plane polarized light the effect of the helical layout of the liquid crystal molecules is to twist the plane of polarization through 90° . Therefore, if a second polarizer is placed at the output side of the cell with its direction at right angles to the first the maximum amount of light will be transmitted with no electric field applied. When an electric field is applied the molecules move towards an orientation perpendicular to the windows, this reduces the twisting effect and the transmission of the system is reduced and ideally extinguished with full drive.

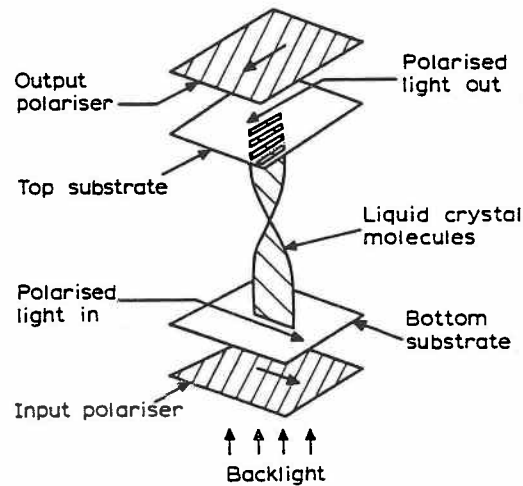


Figure 1.5: Electric field effects on liquid crystal

At intermediate drive levels the situation is more complicated because the molecules will be tilted by complex angles, leading to unequal treatment of light in different directions. The resultant optimum viewing angle will be perpendicular to the average direction of the molecules at the centre of the cell, somewhere along a plane at 45° to the rubbing angles and the polarizers. If the cell is constructed as shown in Figure 1.5, with the direction of rubbing of the alignment layers and the polarizers at 45° to the sides of the display, the direction for optimum viewing will be found by tilting the display backwards.

1.3.1.1 Active matrix addressing

Figure 1.6 shows the switching of an LCD cell. To address a pixel the appropriate video voltage is established in the column. The electronic switches are turned on and the

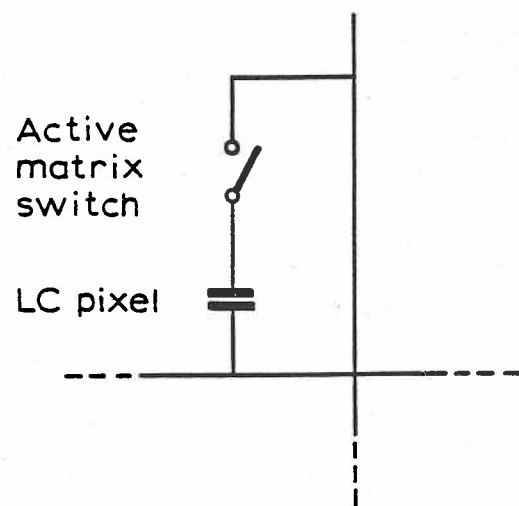


Figure 1.6: Addressing of liquid crystal cell

current which flows charges the pixel capacitor, to a value determined by the column voltage. When the addressing is complete the electronic switches are turned off, as a result, any further changes in the column voltage do not cause a change in the voltage across that particular pixel.

If the cell is driven correctly, the light it transmits should have a minimal 50 Hz flicker which is not visible. This flicker is not of the magnitude of the CRT, so should not present the problems mentioned in section 1.2.1.

1.3.2 Other LCDs

Active matrix addressed displays using the standard twisted nematic liquid crystals are at present the most important technology for high quality LCD television displays. Other types, such as ferro-electric or super twisted nematic which are used for datagraphics with limited grey scale capability, will have similar measurement requirements.

A further class of LCD is the polymer dispersed liquid crystal panel. Its operation depends on the different scattering characteristics, with and without an electric field applied, of liquid crystals dispersed in a polymer. These do not rely on polarization and so are capable of high contrast ratios. It is also claimed that they can be made in large sizes. The measurement problems would be similar to those already met with the colorimetry of diffuse scattering samples.

1.3.3 Potential sources of measurement error

Light from the LCD is not a sharp scanning spot as is the case with the CRT. Provided that the LCD is correctly adjusted it will produce an almost constant level of light rather than a series of sharp pulses. LCDs are less bulky than CRTs and free of high voltages making them easier to mount in measurement systems.

1.3.3.1 Spectral power distributions

The spectral power distribution of light emitted, or reflected from an LCD will be related to the spectral power distribution of the light source used to illuminate the display and the spectral transmission of the mosaic colour filters used to bring colour to the display. The fluorescent backlight will have the mercury spectrum with its strong emission lines in the blue, green and yellow, together with the spectrum of the phosphor coating inside the lamp which will probably have a strong narrow red emission line. Some colorimeters or colorimeter calibration checks are designed for a standard television phosphor set, so will give systematic errors when used for measuring LCDs.

1.3.3.2 Angle

Another potential cause of error is that colour, contrast and brightness of an LCD will vary with viewing angle. This means that both the angles of azimuth and inclination at which the measurements are made together with the numerical aperture of the measuring system must be carefully specified. For any given application there will be a finite cone of angles for which the measurements will be valid. For direct view panels this angle could be as small as $\pm 0.2^\circ$ but for panels with projection systems the angle could be as high as $\pm 10^\circ$. When this angle is specified, the numerical aperture required of the measuring device must also be specified. Addendum 1 to ISO 9241 will produce a useful guide for the specification of angles.

1.3.3.3 Polarization

Light from the LCDs is usually polarised and therefore the measuring equipment should not be sensitive to the direction of polarization. In many monochromator systems the degree of polarisation is wavelength dependant, therefore a simple wavelength independent correction factor cannot be used.

1.3.3.4 Temperature

The performance of LCDs is very temperature sensitive. Temperature effects the viscosity of the liquid crystal and thus changes switching times and other factors like contrast. Projection systems using LCDs should be given time to warm up prior to measurement and room temperature should be recorded during the measurement.

1.3.3.5 UV and NIR emission

A lamp used to illuminate an LCD may emit invisible radiation in the infrared or ultraviolet. Though this is invisible to the eye, it may not be to the measurement system and can therefore lead to errors. If the source is located behind the liquid crystal, the glass structure will probably absorb most of the UV, but not the infrared.

1.3.3.6 Fluorescence

Fluorescence is the mechanism whereby light is absorbed at one wavelength and re-emitted at another of lower energy - for example UV may be re-emitted as blue, or green may be re-emitted as red. Some dyes used in LCDs are fluorescent. If the display is calibrated with a built in light source and there is negligible ambient light falling on the display, the fact that the display uses fluorescence is not a problem. However, if the display is used in a reflective mode, it is not possible to simply measure the spectral reflectance of the display and multiply this by the spectral power distribution of a source to give the colour of the display for that particular source. In this case, the display must be measured using the intended illumination source.

1.3.3.7 Photosensitivity

The active switching technology in LCDs can be photosensitive, and thus its operation is dependant both on any light generated by the display, and ambient light. If the display is to be used in an environment with a high level of ambient light, it should be measured under this high illumination level.

1.4 OTHER DISPLAY TECHNOLOGIES

It is not the aim of this report to list and detail the functioning of all current display technologies.

It is the intention that the reader should use the measurement errors set out for the three display technologies described above as a guide to measurement errors likely to be present when measuring other display types.

2 CURRENT REQUIREMENTS AND POSSIBLE FUTURE NEEDS FOR THE CALIBRATION OF VISUAL DISPLAYS

Now more than ever before, use of colour in displays requires accurate colour measurement. This chapter examines the reasons why good colour measurement of displays is so important and will become increasingly so in the near future.

2.1 INTRODUCTION

There is no doubt that the number of visual displays in use is increasing and will continue so to do. Every aspect of western life seems to include the use of information displays. Such a thriving industry generates many competing technologies, each with specific technological pros and cons, each with distinctive metrological problems. The introduction of colour into such systems can greatly increase their efficacy, (MacDonald 1990). The colours used in applications are rarely arbitrary (Displays 1990), an example being a military information display system where a range of colours are used to code in highly specific ways. Icons of similar colour group together, others are coloured so as to instantly grab a viewers attention. Such carefully designed colour sets must be faithfully reproduced or the ergonomic scientists' work will have been in vain. This demands good colour measurement.

As displays become more stable, it becomes plausible to use them in applications demanding reliable colour reproducibility. Software exists within the printing industry to emulate the colour appearance of prints under different illuminants on CRT based CAD systems. Similar renditions are used in the textile industry (Hawkyard 1991). These high quality CAD applications rely on monitors displaying the 'right' colours. Another example of critical use of colour displays is in the field of human vision experimentation. The fundamentals of colorimetry were based on experiments performed with complex lamp based instruments which can only produce very simple test patterns. Displays in vision experiments are simpler to program, are more versatile, less likely to break down and can show complicated test patterns which may relate better to 'real world' conditions. However, the results are often only as good as the colorimetric calibration of the display.

2.2 FUTURE NEEDS

In the future, we can expect displays to become more reliable, more stable, more diverse in their technology. Colorimetry will play an even more crucial role for both the vendor and the user. We are already seeing practical applications unheard of ten years ago: virtual reality, electronic paper, flat panel displays, full colour desktop publishing systems, colour image analysis and remote sensing in on-line systems, Internet conferencing, colour faxing and telepresence in colour critical applications such as surgery. If we are to rely on colours rather than have them as a classy bonus, then it will become increasingly important that colours are accurately reproduced.

The introduction of quality systems tightens up the way that measurements are made, requiring formalisation and provenance. An increasing number of laboratories are finding that their quality systems require proof of traceability of scales to National Standards. This increases the number of measurements made within the National Measurement System. (See Chapter 8 for further information).

Technological advances are also being made in the field of measuring apparatus. An example is the CCD array. This affords high spectral and/or spatial resolution so might be used to examine spatial uniformity of a display. Quality systems must be confident that these new instruments can be incorporated into the National Measurement System - that the results can be related to National Standards.

It has long been known that colour specification models are a very simple imitation of some aspects of human colour vision. In recent years more elaborate models describing the phenomena of 'colour appearance' (see Chapter 3) are being developed. In these, evaluating the specification of a colour of an area will not just be a case of quantifying the proportions of red, green and blue light within that area. Other factors such as the sample media, the colour of the region surrounding the test area, and the luminance level will affect the specification of the perceived colour. If a meter is to be made to measure colour appearance, it is important that a way of calibrating such devices, and relating their scales to the National Measurement System is made available.

2.3 AWARENESS OF MEASUREMENT PROCEDURES

There are several different technologies available for performing colour measurement of displays: tristimulus filter colorimeters, scanning spectroradiometers, and diode array devices. However there are few publications dealing specifically with approaches to colour measurement of displays and the errors and pitfalls to avoid. Light from displays can be polarised, pulsed and spectrally complex. Colours on displays can be unstable, sometimes varying on a daily basis or after rotating the display. The accuracy of values given by an instrument is dependent on a number of factors. Errors need to be quantified, particularly if the measurement facility are to be subjected to the rigours of a good quality assessment system, such as ISO 9001, or to the more technical rigours of NAMAS accreditation. This document outlines these errors and suitable procedures for the colorimetry of displays.

2.4 CRTS

The current requirement for the colorimetry of CRTs depends on the type of display and the application. At present the largest application of CRTs is for **domestic television**. Probably the second largest use will be for **personal computers** where for the overwhelming number of applications precise colorimetry should not be necessary. The smaller, but significant, professional market for either **high quality studio monitors** or monitors for the air traffic control type of application may need more accurate colorimetry. In addition **computer aided design** is being used for applications such as printing and textile design where the colours on the monitor need to relate to those of the real article under some standard illuminant.

2.4.1 Domestic television

For the major part of the domestic market for televisions, colorimetry can be satisfied by tristimulus colorimeters or even cheaper colour analyzers which just detect differences from a predetermined norm, the emphasis being on high speed and low cost. For these measurements some form of calibration checking is needed for the colorimeters but it is probably safe to assume that standard television phosphors have been used which have well known spectral power distributions.

2.4.2 More colour critical uses of CRTs

Colorimeters can still be used for colorimetry by the computer aided design and high quality display market, but more careful checking may be necessary. A spectroradiometer may be needed to measure the spectral power distribution of the phosphors.

The range of computer supported applications where colour selection and manipulation is a natural characteristic of the user's task is large, and includes such disciplines as graphic, architectural, textile, product, interior, and engineering design. In addition, colour is proving to be useful, or desirable in applications where colour was not available in the past (e.g. business support, management information, and office systems). It is not unreasonable to assume that all future computer systems will be colour systems.

The typical problem in using these systems is the poor colour fidelity across different systems. Users and developers both want 'what you see is what you get' (WYSIWYG) on systems. A computer user might spend hours, painstakingly choosing and balancing colours in order to create an image, and then spend only a minute to print out a hard copy. If the hard copy does not maintain the user's carefully achieved colour balance, the entire image can be rendered useless. Similarly, when a colour image is displayed on a monitor which is different from the one used to create the original image, the colour appearance between two images could be very different. When colour mismatching occurs, the impacts are both practical and aesthetic. The common approach to overcome this is to adjust colours on screen interactively until a satisfactory match is obtained. This not only greatly reduces users' confidence in making colour decisions from the screen but also limits their efficiency. It is estimated that in some industries there is a 30% overhead due to redesigns needed to correct colour reproduction problems.

2.5 DEVICE CHARACTERISATION

The graphic arts industry desires high colour fidelity and has a great interest in the area of electronic data movement, from creative design through to final printing. Currently, there are several international standard activities taking place in this field. (Appendix B gives a brief account of various activities in standardization.) The initial thrust of these standards was simply the movement of data. However, as these needs have been met there has come the realization that the meaning of the data being transported must be defined better to achieve WYSIWYG colour. There are many researchers and industrialists already active in this type of research known as *device characterisation*.

Device characterisation usually involves the derivation of mathematical functions which transform between the *device dependent coordinates* and a CIE colour space. (Colour specification in a computer-based system usually uses the coordinate system of the output device, such as red, green, and blue for a monitor, or cyan, magenta, yellow and black for an electronic printer. These colour specification systems are known as device dependent systems).

2.6 LCDS

The LCD principle is being applied more and more to emulate - perhaps supersede - the CRT. More and more full colour devices use LCDs - video phones, miniature TV receivers and portable computers. Many feel that this is the technology which will be used in the long term to achieve the full colour flat panel hanging on a wall. As the technology continues to evolve, single LCD pixels are tending to get smaller, while the display as a whole is getting larger. If the

LCD does become the CRT of the future, then a much higher volume of measurement will be performed on them, at the research and development stage, on the production line and in the application.

2.7 COLORIMETRY IN AVIONICS

Avionics is a large industrial sector. It is hoped that this section will be helpful both to those within the industry, and to those outside, as an example of how to tackle a complicated measurement scenario. This section covers the problems encountered by a colorimetrist within a particular environment, and sets out how measurements of the variety of displays within that environment might be achieved.

2.7.1 An example environment: Aircraft cockpit

The modern aircraft cockpit is full of controls and displays with a wide variety of functions but all have the purpose of conveying visual messages to the aircrew which can be assimilated quickly, accurately and without ambiguity.

The variations in luminous environment are extreme, ranging from the aircrew adapted to a completely dark external environment through to full exposure to high-altitude solar illumination.

Colour plays an important part in such displays but is not necessarily the most important attribute - resolution, geometric accuracy and dynamic response can be more critical drivers.

Colour is mainly used as a means of grouping the information into operationally meaningful categories, de-cluttering a complex display (while observing existing colour associations such as 'red for danger'). In addition 'false-colour' techniques may be used, for example to represent the temperature scale of a thermal-imager.

Colour fidelity as such is rarely a requirement but colour consistency is needed.

The multiplicity of light sources in the cockpit will represent many different technologies from many different vendors, but despite this the cockpit designer has to ensure that:-

- A colour having a particular operational significance is always recognised as belonging to the correct category.
- Colour **verification** amongst a group of light sources should not give rise to an apparent but spurious significance.

2.7.2 Scope

The scope of colorimetric measurements in avionics is not confined to emission measurements on well known display devices such as CRTs and LCDs.

It also embraces:-

- Back illuminated fixed legends and scales which are visible at night by virtue of their emission and in daylight by virtue of their reflectance.

- Individual indicator lamps.
- The reflectance properties of all display devices since visibility in high illumination conditions is mediated by the ratio of emitted to reflected light. Reflective properties do not need to be measured to high accuracy, but proof that the reflectance is less than 1% often needs to be established.
- For engineering purposes candidate components and materials need to be measured. For these purposes it is often essential to obtain spectroradiometric data.
- For military applications it is increasingly necessary to control the display emission in the near infra-red. Strictly speaking this is outside the field of colorimetry, but cannot be ignored.

2.7.3 Choice of instruments

There are two types of instrument which can be used to calibrate airborne displays - the colorimeter and the spectroradiometer.

The colorimeter is:-

cheap, compact, and easy to use but prone to errors from imperfect matching of the CIE tristimulus functions.

The spectroradiometer is:-

Expensive, cumbersome, slow but essentially free from tristimulus matching errors.

In principle, the errors of a filter colorimeter could be calibrated-out by characterising the instrument response on a typical display against a reference spectroradiometer. However, in the avionics business there are relatively small production quantities of many product variations. Even within CRT technology eight different phosphor spectral distributions compounded by different filter characteristics can be used. In addition other display technologies such as tungsten-lamps, LEDs, LCDs and EL panels are employed making it necessary to calibrate the colorimeter for each type of display. Avionic displays are generally not portable, requiring several additional instruments to support their operation. Calibration of these displays on a regular basis at a National Standards laboratory could be seen as an impractical procedure.

Due to the difficulties outlined above, spectroradiometric instruments are used to calibrate these types of displays. For routine production measurements where speed is an economic necessity, the diode-array type instruments are used.

For engineering design investigations, a conventional scanning spectroradiometer is used for the more demanding tests and a diode-array type for tests where speed of measurement is more important (eg. measuring colour change as function of time).

To support wavelength and spectral radiance calibration of the spectroradiometers, in-house standards traceable to national standard are used.

3 COLORIMETRY AND COLOUR APPEARANCE

A system of units has been developed by the CIE which can be used to uniquely specify colour. It should be emphasised that the CIE system concerns itself only with colour matching not with colour appearance. Two colours which are matched in CIE colorimetry will be visually matched if viewed in exactly the same total visual context.

The perception of colours under different visual contexts is the subject of Colour Appearance. Colour Appearance takes into account factors such as surround effects, chromatic adaptation and lightness level.

3.1 THE CIE SYSTEM OF COLORIMETRY

By far the most important of all colour specification systems is that developed by the Commission Internationale de l'Eclairage (CIE). It provides a standard method for describing the colour stimulus under controlled lighting and viewing conditions. The CIE system is derived from careful psychophysical experiment, is thoroughly documented within CIE Publication 15.2 and has the force of an international standard. It has, therefore, become the basis of all industrial colorimetry (Hunt 1991).

In 1931, the CIE recommended the use of three standard illuminants in terms of spectral power distributions, known as A, B and C, corresponding to incandescent light, direct sunlight, and average daylight respectively. The standard observer functions $\bar{x}$, $\bar{y}$ and $\bar{z}$, based on the experimental results of Guild and Wright (Wright 1969), were also established to represent the average visual response of the human population having normal colour vision. Additionally, the CIE standardised the illuminating and viewing conditions for the measurement of the reflectance of a surface. Thus the colour of any object can be specified by a triad of numbers (X,Y,Z) called tristimulus values (eq. (1)). These are computed as the summation of the products of the spectral power distribution function (S) of the illuminant, the spectral reflectance function (R) of the object, and the standard colorimetric observer functions (x,y,z) across the wavelength range of the visible spectrum. CIE publication 15.2 states that the wavelength range 380 to 780 nm is sufficient for most applications.

$$\begin{aligned} X &= k \sum [S(\lambda) R(\lambda) \bar{x}(\lambda) d(\lambda)] \\ Y &= k \sum [S(\lambda) R(\lambda) \bar{y}(\lambda) d(\lambda)] \\ Z &= k \sum [S(\lambda) R(\lambda) \bar{z}(\lambda) d(\lambda)] \end{aligned} \quad \text{---- (1)}$$

The k constant was chosen so that Y = 100 for the perfect reflecting or transmitting diffuser.

The CIE system was extended in 1964 to include a new set of colour matching functions (called the CIE 1964 supplementary standard colorimetric observer), to cover the viewing field in excess of 4°, and a new illuminant (D65) together with a series of D illuminants to simulate the near-ultraviolet spectrum of daylight better than that of illuminant C.

The two types of instruments frequently used for measuring display colours: a spectroradiometer and a tristimulus colorimeter, will be thoroughly discussed in Chapters 4 and 5. A spectroradiometer will measure the spectral radiance (or irradiance) of a target stimulus directly. Tristimulus values can be calculated using eq. (2) since illuminant and object data are not required for self luminous colours. The areas of colours considered in

display applications usually have quite small angular subtense and the CIE 1931 standard colorimetric observer (2° field) is the appropriate one to use.

$$\begin{aligned} X &= k \sum [P(\lambda) \bar{x}(\lambda) d(\lambda)] \\ Y &= k \sum [P(\lambda) \bar{y}(\lambda) d(\lambda)] \\ Z &= k \sum [P(\lambda) \bar{z}(\lambda) d(\lambda)] \end{aligned} \quad \text{--- (2)}$$

The k constant is again chosen so that $Y = 100$ for the appropriate reference white, ie. having the same colours as illuminants D50, D65 or 9300K. Tristimulus colorimeters generally incorporate a set of filters designed to match as closely as possible the spectral functions of the CIE 1931 standard colorimetric observer. The CIE colorimetric values and luminance can then be measured directly with no need for spectral data or additional calculations.

Colour as described in the CIE system is usually plotted on the chromaticity diagram (see Figure 3.1). The chromaticity coordinates are calculated using eq. (3).

$$\begin{aligned} x &= X / (X+Y+Z) \\ y &= Y / (X+Y+Z) \\ z &= Z / (X+Y+Z) \\ \text{and } x + y + z &= 1 \quad \text{--- (3)} \end{aligned}$$

The region of all perceptible colours is bounded by the horseshoe-shaped locus of pure monochromatic spectral colours (the spectrum locus), with a straight line connecting the chromaticity coordinates of extreme red and blue. White lies near the centre of the figure, and colours become more saturated towards the periphery. The colours of a black-body radiator with increasing temperature follow a curve from deep red through white towards blue. Colours are commonly represented in terms of their chromaticity and luminance (x, y, Y).

When the coordinates of typical real phosphors in a display are plotted in the chromaticity diagram, they form a triangle due to the additive characteristic of three phosphors (see Figure 3.1). This triangle represents the gamut of all colours achievable from a particular display and is well inside the spectrum locus. The colours outside the range of triangle are known as out-of-gamut colours, ie. colours which could be seen by the human visual system but cannot be produced by the display. It is tempting but misleading to

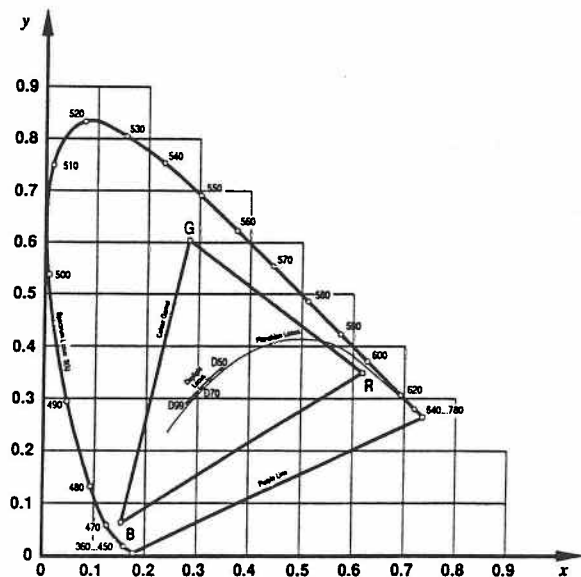


Figure 3.1: The colour gamut of a display plotted in CIE 1931 chromaticity diagram.

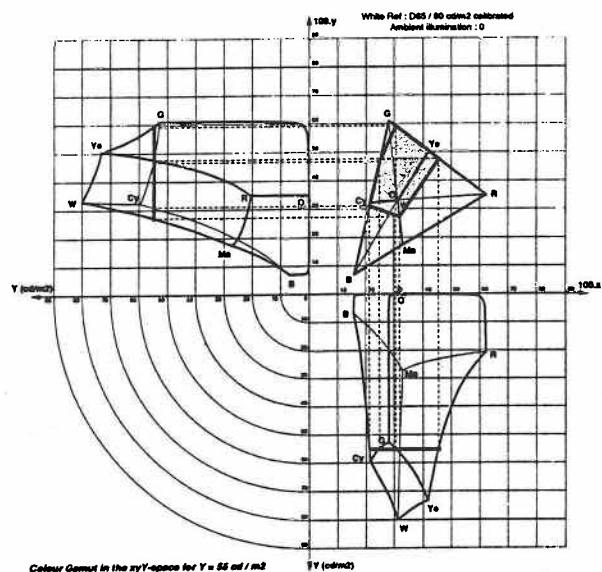


Figure 3.2: Full gamut of colours displayable on a CRT

regard the interior area of the chromaticity triangle as representing the full range of colours that can be produced on a display, because each of the primary colours occurs at a different luminance level (Y). In three dimensions (say xyY space), the display gamut is seen to be akin to a truncated triangular pyramid, where at high luminance levels the colour range is very restricted. This is well illustrated in Figure 3.2.

The range of colours obtainable from monitor phosphors depends on the luminance level. The colour solid in xyY space clearly shows how the chromaticity diagram shrinks from the full triangle to a single point at white. (Courtesy of Barco Graphic Displays)

3.2 COLOUR DIFFERENCE FORMULAE

The CIE system offers a precise means of specifying a colour stimulus under fixed viewing conditions, thus making it an excellent choice as a reference for industrial colour communication. Another important use of colorimetry is to evaluate colour-difference for industrial colour quality control. Many sets of colour discrimination results have been established, which show that the tristimulus colour space has poor uniformity, i.e. some colour differences perceptually equal in size could give a ratio of 30 to 1 in the chromaticity diagram.

In 1976, the CIE recommended two uniform colour spaces: CIE L*u*v* and CIE L*a*b* together with colour difference formulae. The CIE L*u*v* system is used for additive colour media, including coloured lights and emissive phosphor displays and is a linear transformation from the tristimulus space.

The definition of CIE L* u* v* begins with a linear transformation of the x, y chromaticities: as shown in eq. (4).

$$\begin{aligned} u' &= 4X/(X+15Y+3Z) = 4x/(-2x+12y+3) \\ v' &= 9Y/(X+15Y+3Z) = 9y/(-2x+12y+3) \end{aligned} \quad \text{----- (4)}$$

to obtain x,y from u', v' the following equations are used:

$$\begin{aligned} x &= 9u'/(6u'-16v'+12) \\ y &= 4v'/(6u'-16v'+12) \end{aligned} \quad \text{----- (5)}$$

The x,y and u',v' chromaticity diagrams show additivity - that is that additive mixtures of colours are represented by points lying on a line joining points representing the constituent colours. The position of the mixture colour can be calculated simply in the case of x, y by the ratio of luminance values of the two points, ie if colour C₁ has luminance M₁ and colour C₂ has luminance M₂ then the ratio of the length of C₁C₂:C₂C₃ where C₃ is the resultant colour will be M₂/y₂:M₁/y₁, where y₁ and y₂ are the respective luminances.

CIE L'u'v' is a system used for describing nominal colours. CIE L*u*v* compares one colour with another (usually a reference white - see Table 2.1).

White	Application
D50	Graphics arts.
D65	Usual broadcast white, recommended by 9241.
D93	Recommended by 9241.

Table 2.1: Common white points and their applications. The chromaticities of these whites appear in the literature (eg Wyszecki & Styles 1982).

CIE L*u*v* Formula

$$\begin{aligned}
 L^* &= 116(Y/Y_0)^{1/3} - 16 & \text{for } Y/Y_0 > 0.008856 \\
 u^* &= 13 L^* (u' - u'_0) \\
 v^* &= 13 L^* (v' - v'_0)
 \end{aligned}
 \quad \text{--- (6)}$$

where u' , v' , Y and u'_0 , v'_0 , Y_0 are the $u'v'$ coordinates of samples and reference respectively. Colour difference can be calculated as:

$$dE = (dL^{*2} + du^{*2} + dv^{*2})^{1/2} \quad \text{--- (7)}$$

Correlates of hue and chroma are defined in CIE L*u*v* by converting the rectangular u^*, v^* axes into polar coordinates using equations (8). These perceptual dimensions permit them to be used in a similar fashion to other polar based systems such as NCS (Natural Colour System) or Munsell colour spaces, but with the added advantage of being able to relate the coordinate values back to precise colorimetric specifications.

$$\begin{aligned}
 \text{Hue:} & \quad h_{uv} = \arctan(v^*/u^*) \\
 \text{Chroma:} & \quad C_{uv}^* = (u^{*2} + v^{*2})^{1/2}
 \end{aligned}
 \quad \text{--- (8)}$$

Hue and chroma are defined by polar coordinates in CIE L*u*v* space.

The range of colours achievable by a particular display is known as the display colour gamut, and it appears as a solid volume in three-dimensional colour space.

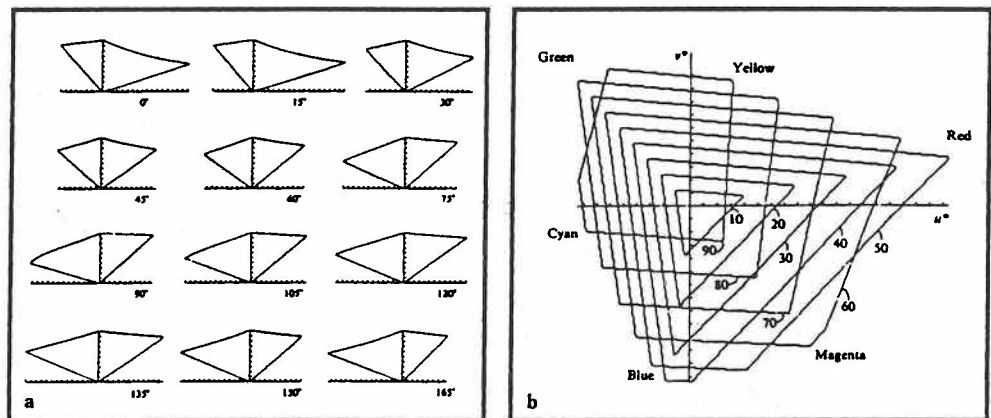


Figure 3.3: Two-dimensional cross-sections through the CIE L*u*v* gamut of a colour display (from Robertson, P57)

dimensional cross-sections of the CIE $L^*u^*v^*$ colour space, particularly planes of constant lightness or constant hue, are commonly employed to visualise the extent of a display's colour gamut (Robertson 1988), as shown in Figure 3.3.

The CIE $L^*a^*b^*$ system is commonly used for subtractive media, where light is absorbed by colorants such as dyes and pigments. It is a nonlinear transformation of the XYZ tristimulus space to simplify the original ANLAB (Adams 1942) formula, which was designed to fit the Munsell spacing and widely used in the colorant industry. (Billmeyer and Saltzman, p57).

Colour difference specification systems are described in detail in the literature. (Hunt 1991)

3.3 CRT DISPLAY CHARACTERISATION

Accurate colour communication across different computer-controlled devices (such as scanners, digital cameras, displays and printers) is required by some computer users. Various national and international standards committees including representatives of the imaging device manufacturers, software engineers and colour scientists have been formed to reach a common agreement on how best to achieve WYSIWYG (What You See Is What You Get) colour reproduction. An essential step of such standards is the transformation of the device dependent colour coordinates (such as the digital to analogue converter (DAC) values of red, green and blue (RGB) for a video display) into the corresponding CIE colorimetric values (device independent specification), or vice versa. This procedure is known as device characterisation.

Various mathematical models have been proposed by Cowan (1983), Post & Calhoun (1989) and Berns et al (1994b) for CRT display characterisation. These models typically include two stages: Stage one is a nonlinear transformation from the DAC values for each of the three channels to the output luminances; Stage two linearly transforms these luminances to the tristimulus values.

Before commencing the modelling, certain colorimetric information needs to be determined, namely the chromaticities and luminances of the three phosphors, plus the white and black points. Each phosphor's chromaticity coordinates are obtained by measuring the colour at maximum DAC signal value (normally 255). The desired chromaticities and luminances of the white and black points can be achieved by interactively adjusting the display's brightness (also called black level or offset), and contrast (or gain) controls.

Once this state is stabilised, the first stage of modelling can begin. It requires measurement of the light output for a series of DAC values applied to each of the RGB channels in turn. Then by plotting the logarithm of the measured output luminances against the logarithm of the normalised DAC values, a simple linear relationship (the 'gamma' of the display) can be derived (see Figure 3.4). If the gamma law held perfectly the graph of log intensity vs log signal would be a straight line. Departures from the straight line sometimes occur at low light levels, however, due to the effects of ambient light and poor linear behaviour of the electron gun. A more reliable model can be developed by fitting a second-order polynomial to the data in log-log space (Cowan 1983). Better results still, (Post and Calhoun 1989, Luo et al 1991a) can be obtained by piece-wise linear interpolation with suitably distributed DAC values, or by a three-dimensional interpolation procedure based on a large number of measurement samples.

In the second stage of the characterisation procedure, the colours generated can easily be calculated in terms of their XYZ tristimulus values from a knowledge of the chromaticity coordinates for the primary colours x_r, y_r for red, etc, and the output luminances (Y_r, Y_g, Y_b) for each channel by means of a 3x3 matrix multiplication (Sproson 1983). It is also customary to normalise the XYZ values to $Y = 100$ for reference white.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} x_r/y_r & x_g/y_g & x_b/y_b \\ 1 & 1 & 1 \\ z_r/y_r & z_g/y_g & z_b/y_b \end{bmatrix} \begin{bmatrix} Y_r \\ Y_g \\ Y_b \end{bmatrix} \quad \text{--- (10)}$$

When a display is characterised, four important assumptions are normally applied (Cowan & Rowell 1986): temporal stability (the same colorimetric properties last over time); spatial uniformity (the same colorimetric parameters are preserved at different positions on the screen); channel independence (the exitance of one channel at a given pixel is not dependent on the other channels at that pixel); and phosphor constancy (the chromaticities of each phosphor are independent of voltage applied to the channels). Each of these dependencies would affect the predictive accuracy of the characterisation models, and various methods have been proposed to measure such discrepancies (Cowan & Rowell 1986, Brainard 1989, and Berns et al 1993b).

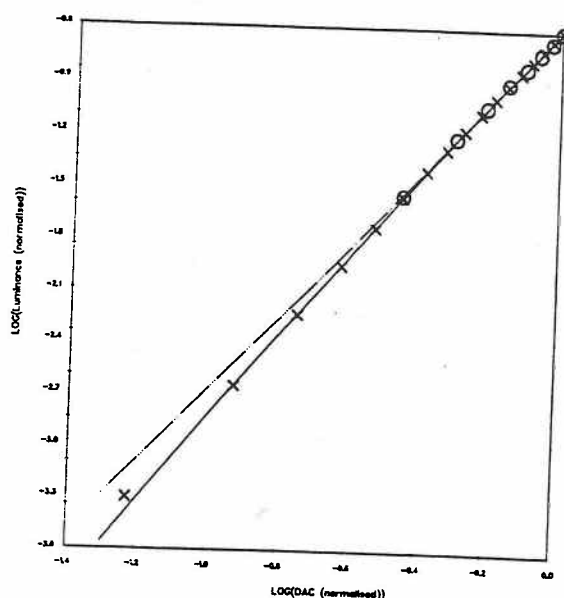


Figure 3.4: Normalised log(luminance) vs log(DAC) data (crosses and circles) measured on a Barco monitor, plotted against best fit linear and second-order polynomials in log-log space.

3.4 COLOUR APPEARANCE

As described in section 3.1, the CIE systems were defined to measure the visual equivalence of coloured lights, and were later applied to the measurement of surface colours and assessment of colour differences between two colorant mixtures on similar media. The systems have proved very successful for comparing, for example, two dyes applied to a similar fabric or two paints applied to a similar substrate. Provided that similar constraints are imposed, the CIE systems can be equally effective as a metric for assessing the accuracy of a colour match in image reproduction on displays.

However, there are still some problems in applying colorimetry (Hunt 1993). In particular, when considering how to achieve WYSIWYG colours (Johnson 1992), four parameters can cause problems: white point equivalence, media differences, measurement geometry, and gamut mapping. A reproduction will look exactly the same as the original image ONLY if both have the same XYZ values for the white point, the two media have similar surface characteristics and are observed under similar viewing conditions, and the reproduction medium can produce ALL the colours present in the original. In practice these parameters can vary considerably from one medium to another as Table 2.2 indicates, with the result that two stimuli presented on different media under distinct viewing conditions will usually not match visually even though they are measured to have identical XYZ values.

Parameter	Real scene	CRT display	Print in Office
Type of medium	Mixed	Self-luminous	Reflective
Dimensions	Dynamic 3-D	Dynamic 2-D	Static 2-D
Illuminant Type	Sun + lights	Self + ambient	Lamps + daylight
Luminance (cd/m ²)	1000 - 5000	50 - 120	150 - 500
White point (K)	200 - 10,000	5000 - 9300	2700 - 5500
Surround	Light	Dark - light	Light
Dynamic range	1000:1	100:1	50:1
Spatial resolution	Ideal	Low	Very low
Colorants	Mixed	Phosphors	Ink pigments
Color gamut	Very large	Large	Medium

Table 2.2: Characteristics of different media

Surround plays an important part in the appearance of colour. The simultaneous contrast effect is well known for a single coloured patch on a coloured background (Albers 1963), but applies also for a complex image. The effect of a dark border, for example, is to make the image appear lighter with less contrast, whereas a light border makes the image appear darker and less colourful. On a display monitor there are typically four concentric zones surrounding the central image area, all of which have an effect on the colour appearance of the image (MacDonald et al 1990).

The most important is the image surround, over which the application designer has full control but is often neglected. The complexity of surrounds is shown in Figure 3.5. The effect of a dark surround is to make the image appear lighter, requiring an increase in the 'gamma'. Conversely, a light surround makes the image appear darker, requiring a decrease in image 'gamma'. A light surround also tends to make the image appear less colourful. The lightness and colour of the monitor faceplate and background, being further away, affect the appearance of the image to a lesser degree but still cannot be ignored. Ideally they should be unobtrusive, neutral in colour and graded in lightness from the image surround (MacDonald et al 1990).

In addition to simultaneous contrast, which results from the juxtaposition of colours within an image, there are several other important parameters that affect the colour appearance of an image. These relate to the

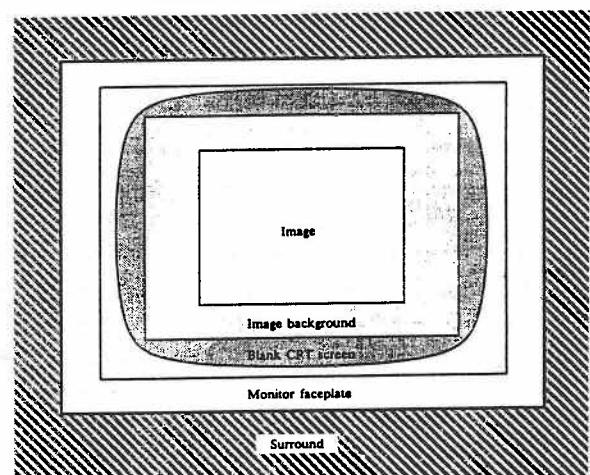


Figure 3.5: Surround regions of a typical display monitor.

nature of the medium or environment in which the image is viewed. For an image presented on a display monitor, in particular, the following factors must be considered.

The brightness, or luminance level of the display affects the apparent colourfulness of colours in the image; the brighter the image, the more colourful it will appear. In general, an image will look more like the original scene if the intensity of the display is adjusted to be closer to the original (Hunt 1987).

The spectral power distribution of the illuminant determines the colour of the reference white in a scene or in a reflection print. On a display, the reference white is determined by the relative gains set for the three red, green and blue electron guns. For computer graphics applications the white reference has typically been 9300K, but for broadcast television D65 (6500K) has been preferred. Sproson suggests that a colour temperature of 5400K would be the ideal for giving the most natural colour appearance, neither too cool nor too warm (Sproson 1983). Methods for calculating the white reference are reviewed by Farrell & Wandell (1993) and Donofrio (1993).

The human visual system is very good at compensating for both the colour and level of the illumination. As a result of this adaptation, objects tend to be recognised as having nearly the same colour in a wide range of conditions, a phenomenon known as colour constancy. The effect is not perfect, for example when transparencies are being projected in a dark room with tungsten light the colour of the screen appears yellowish, especially in the light areas of the image. In general, adaptation to illuminants of different colours becomes less complete as the purity of the colour increases and more complete as the intensity increases (Hunt 1991).

The level and directional distribution of ambient illumination can affect appearance in various ways. For CRT monitors it obviously affects the brightness of the faceplate and background, but also ambient reflection from the surface of the CRT will reduce the image colourfulness and contrast and affect the display gamut (Post & Lloyd, 1994) just as is the case for reflections from gloss on photographic prints. The effect is more marked with diffuse lighting than directional lighting. To compensate for glare, the gamma needs to be increased for dark tones more than for light ones, ie. more for shadow regions than highlights. Close specification over the room lighting and geometry is also desirable, though not always possible to achieve in an office working environment (Travis 1991).

Models of colour vision have been developed by Hunt (1991, 1993, 1994), Nayatani and his co-workers (1987, 1990), and Fairchild and Berns (1993) to predict the colour appearance under the various viewing parameters described above. A CIE technical committee (TC 1.27) has been formed with the objective of recommending a formal method for comparing images between the reflective and self-luminous media. Guidelines have been provided for coordinating research in this area (Alessi, 1994). Some researchers have already conducted the psychometric experiments to test the validity of these models. Luo et al (1991a, 1991b, 1993a, 1993b) applied a magnitude estimation method to investigate the change of colour appearance under a wide range of viewing conditions using reflective, self-luminous, and transmissive media. A simple image was used with a test colour displayed in the middle of the viewing pattern surrounded by a number of decorating colours. These results were used to refine the Hunt model. Fairchild and Berns (1993) also carried out experiments to scale complex images using a pair-wise comparison method. All results suggest that a five-stage transform is required to achieve WYSIWYG colours (Yousif & Luo (1990), Fairchild and Berns (1993), MacDonald (1993)).

4 SPECTRORADIOMETERS

Spectroradiometers measure the amount of light present as a function of wavelength. They are the most accurate means of measuring colour and luminance of visual displays but several factors must be taken into account if they are to be used effectively.

4.1 SCANNING SPECTRORADIOMETERS

A spectroradiometer measures the radiometric output of an optical source as a function of wavelength and minimally contains a dispersing element (monochromator) and a detector. Spectroradiometers can be configured to measure either spectral irradiance or radiance, a limiting aperture is required to measure the latter. Commercial instruments designed with the measurement of displays in mind will incorporate appropriate collection optics which usually include an alignment eyepiece.

Four of the most critical factors of spectroradiometer design are wavelength range, bandwidth, wavelength sampling increment and dynamic range. For colour measurement, the appropriate wavelength range is limited to that of the eye's sensitivity - approximately 380 to 780 nm. However it may not be necessary to measure over this complete range provided that data are collected *well beyond* the limits of the emission spikes of the display phosphors. The choice of measurement spectral bandwidth is a compromise between signal (large band width gives higher signal, thus better signal to noise ratio), and spectral resolution. Wider bandwidths may lead to errors in the calculation of tristimulus values. Ideally wavelength sampling increment should be identical to the bandwidth to avoid over or under - sampling.

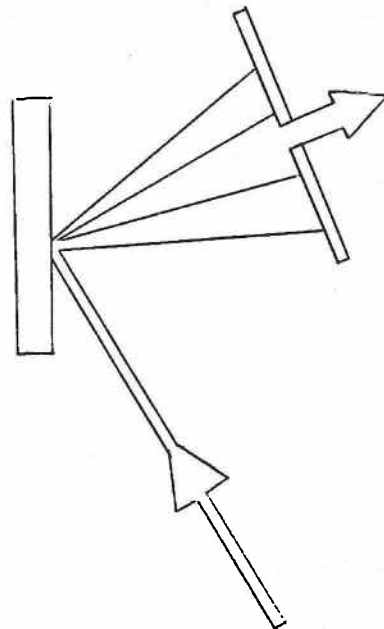


Fig 4.1: Schematic of a monochromator.

The dispersion of light by a diffraction grating is shown schematically in Figure 4.1. Polychromatic light falls on the grating and is dispersed at an angle determined by its wavelength. A slit-width sets the bandwidth of light exiting the system to a detector. The position of the slit (usually the slit is kept fixed while the diffraction grating rotates), determines the wavelength of light selected. Most scanning spectroradiometers use a stop-start method where the monochromator selects a wavelength, a measurement is taken, and the monochromator then moves onto the next wavelength.

It is important that the device has a linear response over the entire dynamic range.

4.1.1 Spectroradiometer bandwidth function

When the display emission contains narrow spectral lines the radiance associated with each line can be in error if there is not a proper relationship between the monochromator band pass shape and the wavelength sampling interval. Ideally the bandwidth should be an integer multiple of the sampling interval.

For a monochromator with a triangular band pass function (which is common), the full width at half maximum should be an integer multiple of the wavelength recording interval. Failure to observe such a relationship can result in spectral lines being under-recorded or over-recorded yielding significant chromaticity and luminance errors. However, this assumes that the function is perfectly triangular. Due to this problem and difficulty in matching the bandwidth to the step interval, the most accurate technique is to continuously scan through the wavelengths and integrate results over desired intervals. Using this method, the shape of the band pass function becomes irrelevant. It is suggested that for good colorimetric calculation, intervals of no wider than 5 nm should be used.

In some instruments this proper relationship is taken care of by the instrument manufacturer and is transparent to the instrument user. However other instruments may, in the interests of application flexibility, allow the instrument user independent access to bandwidth and sampling interval.

4.1.2 Spectroradiometer dynamic range

The dynamic range of this type of instrument will be defined by the peak spectral radiance at which the detector becomes non linear and the noise floor of the system. The actual dynamic range available varies enormously between instrument designs.

It is important to note that displays like CRTs are highly variable in output over a refresh cycle. The light level can vary by a factor of 1000:1 over one refresh cycle (typically 60 Hz). A detector such as a photomultiplier tube will have very fast response and will 'track' this output well. When the signal is later processed by electronics, it becomes time filtered and the sharp sawtooth wave becomes a ripple. Care should be taken that the detector is not saturating at the pulse peaks. A suitable test is to determine whether the system is operating within its linear range is to view a display through a series of optical filters with known transmittance. These filters should range in optical transmittance over a wide range: typically 100% (no filter) to 0.01%.

4.1.3 Wavelength

Correct setting of the wavelength scale of a spectroradiometer is crucial. A study on the effects of wavelength errors in spectroradiometers when measuring displays (Berns 1993) showed that a wavelength shift of ± 0.5 nm over the whole measurement range can result in a change of $1.8 \Delta E^*_{ab}$ units (corresponding to twice a just noticeable colour difference), for a blue phosphor of a CRT. (For the red and green phosphors the values were 0.3 and 1.1 respectively). Larger errors can occur if the wavelength shift varies through the spectral range.

The dispersing element in a monochromator - a diffraction grating - is rotated to vary the part of the spectrum entering the detector. If the rotation mechanism is not linear then wavelength inaccuracies may occur over part of the available range. The wavelength accuracy

should be checked at several wavelengths across the range. The range may also be linear, but have an offset, or linear with the incorrect ratio of grating degrees rotation to intended wavelength.

Wavelength scale and band pass function are typically assessed using sources with spectral line output such as low pressure mercury, neon, or mercury cadmium mixes. Values for the position and intensity of these spectral lines are well known (MIT 1969). Following these checks a correction can be made to the wavelength scale.

4.1.4 Measurement area

It is important to ensure that the aperture of the measuring instrument is fully filled. The spectroradiometer responsivity is unlikely to be uniform over the input aperture and so it is not possible simply to apply a detector 'fill factor' correction if it is not fully filled.

Often a fibre optic bundle, or a transmitting diffuser is used as a spatial 'scrambler'. This scrambler can also depolarise incident light which might otherwise result in errors due to the polarisation sensitive diffraction grating. The efficiency of the randomising element can be investigated by checking that there is no image of the source at the plane of the detector. The depolarisation effect can be checked by rotating a polariser between the instrument and light source to see if there is any significant variation in signal level with polarisation orientation.

4.1.5 Calibrating radiometric scale of spectroradiometers

A detector will generate a noise signal - called a dark current - which is usually independent of wavelength. Additionally the whole spectroradiometer system will have a sensitivity which varies with wavelength. The dark current is determined (V_{noise}) by measuring the signal with the instrument aperture blocked. The sensitivity as a function of wavelength, $\text{Sens}(\lambda)$, can be found by measuring a 'standard lamp' whose spectral output has been calibrated, $L(\lambda)$, and comparing the measured signal $V_{\text{sig}}^L(\lambda)$, to the known spectroradiometric value (in, say $\text{mW}/\text{m}^2/\text{nm}$):

$$\text{Sens}(\lambda) = L(\lambda) / [V_{\text{sig}}^L(\lambda) - V_{\text{noise}}] \quad \text{for the standard lamp}$$

Having established the sensitivity of the system, measurements may now be made of a display and the results reported in useful units:

$$\text{Value}(\lambda) = \text{Sens}(\lambda) * [V_{\text{sig}}^D(\lambda) - V_{\text{noise}}] \quad \text{for the display}$$

Ideally the calibration source should have a stable spectral power distribution which is comparable to the display. Such sources are not currently available. Sources traditionally used for the calibration of spectroradiometers are tungsten lamps powered by stabilised electrical supplies. As calibration source and display often have quite different spectral power distributions, accurate measurement relies on the linearity scale of the spectroradiometer.

The standard lamp will usually illuminate an opal or white tile at normal incidence, with the detector viewing the diffuser at 45° to ensure a uniform field. Alternatively, the lamp is placed within an integrating sphere. (This arrangement is often called a 'luminance gauge'). The interior wall of the sphere is coated with white paint and is evenly illuminated due to multiple reflections. A port on the sphere wall acts as a 'secondary source' and is viewed by the detector. The integrating sphere method has the added bonus of ensuring that the

reference source is randomly polarised.

4.1.6 Stray light

Light falling on a diffraction grating diffracts off at an angles dependant **only** on wavelength, (Lothian, 1975), providing the grating is perfect. However as gratings are not perfect, there is a small additional scatter of light at other angles which, for a white light source, will add to the selected wavelengths exiting a monochromator. This so called heterochromatic stray light can be reduced by sending the light exiting a monochromator to a second monochromator tuned to the same wavelength. The portion of heterochromatic stray light exiting the second monochromator will be significantly less than the first though the overall light level will also be reduced.

Heterochromatic stray light may be checked using blocking filters. The monochromator is set to a wavelength just below the cut-off point of the filter, the filter is inserted between grating and detector. Any signal recorded is due to stray light at higher wavelengths.

A second type of stray light, caused by second and higher order spectra diffracted by the diffraction grating can also pass through the monochromator exit slit. This light is largely removed by placing an 'order sorting filter' at the entrance port.

4.2 DIODE ARRAY SPECTRORADIOMETERS

4.2.1 Description

The main advantage of using a diode-array type of instrument is speed of measurement.

The conventional spectroradiometer has a single detector channel placed at the exit slit of a monochromator, which is mechanically scanned across the wavelength range. The time to perform a complete measurement is lengthy because at each wavelength step there has to be:-

- Time to execute the mechanical motion
- Time for the detector response to settle to the new signal level
- Time for signal averaging to obtain the desired signal/noise ratio

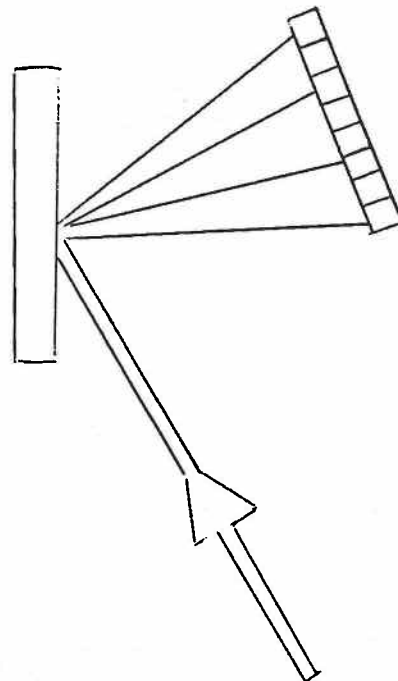


Figure 4.2: Schematic of a diode array spectrophotometer.

A complete set of measurements can take from a few minutes to a few hours.

In contrast the diode-array instrument has an array of detectors at the monochromator exit with each detector associated with a narrow wavelength range (as shown in Figure 4.2). Thus there is no mechanical motion and the settling/averaging process can take place

simultaneously at all wavelengths - providing a parallel rather than serial operation.

Complete measurements are then on the time scale of a few tens of milliseconds to a few minutes.

In addition the absence of precision mechanical motion can lead to both a more compact instrument and to a lower cost instrument.

Whilst this document's primary interest is in the colorimetry of visual displays, it is worth noting that the array detectors used in these instruments are silicon which means that they can have a measuring range between 200-1100 nm.

The detector is often mounted in a sealed housing that facilitates thermoelectric cooling which means that it can be operated between 20 °C and -40 °C minimising noise and maximising stability. Second order rejection filters are sometimes fitted over some parts of the diode array.

Modern diode array spectroradiometers are direct descendants of the Array Spectrometers (Optical Multichannel Analysers) used in chemical analysis and process control etc. They have in the past been used to check that reactions have occurred or objects have a particular emission. By the addition of suitable receptors and calibration sources they have become quantitative devices. The use of an integrating sphere or a cosine receptor makes it suitable for spectral irradiance measurements; alternatively telescope or microscope optics enable spectral radiance to be measured.

Typically, for display measurements a high efficiency telescope would be used with interchangeable apertures ranging from 2' to 3° acceptance angle.

A detector interface unit is sometimes provided to acquire and store data from a linear detector in the measuring head. A "host" computer reads and processes this information and controls the data acquisition process. The computer enables the user to program a range of experiments covering such parameters as:

- 1) The collection geometry.
- 2) The number of scans and integration time.
- 3) The method of initiating the measurement sequence, time, internal or external synchronisation.
- 4) The wavelength range.
- 5) The analysis of acquired data.
- 6) Calibration.

Inevitably there is a price to pay for these advantages, which is touched upon in the following sections.

4.2.2 Potential drawbacks

The following comments are based on experience of a limited range of instruments of this type. The comments are therefore rather specific but are believed to be general to the genre.

4.2.2.1 Timing

Each detector is a silicon photodiode in which the photo current is used to charge its

electrical capacitance. At the start of the measurement cycle each capacitor is restored to a known fixed voltage. Thereafter for a known period (the exposure time) the photo current is integrated in the capacitance. At the end of this exposure period all the resultant detector voltages are rapidly read by an A/D convertor into the associated processor.

The exposure period is often chosen to suit the brightness of the test item, using short periods for a bright source and long periods for a dim source so that the strongest spectral components give rise to detector output voltage near the top of the dynamic range.

However, when measuring a highly pulsed light from a display, the exposure time should be an exact integer multiple of the display refresh period. The instrument user should be satisfied therefore that the instrument design allows this constraint to be met. Longer measurement times mean that more refresh cycles are measured so error due to a non-integer number of cycles is less significant. At higher luminances where measurement times are necessarily short however, some form of synchronisation is essential. Figure 4.3 compares results measuring similar whites with, and without synchronisation of detector to display. Note that the word synchronisation in this context indicates that the measuring apparatus sampling time is directly related to the refresh rate of the display, not that the measurement is initiated at a particular time in the display cycle.

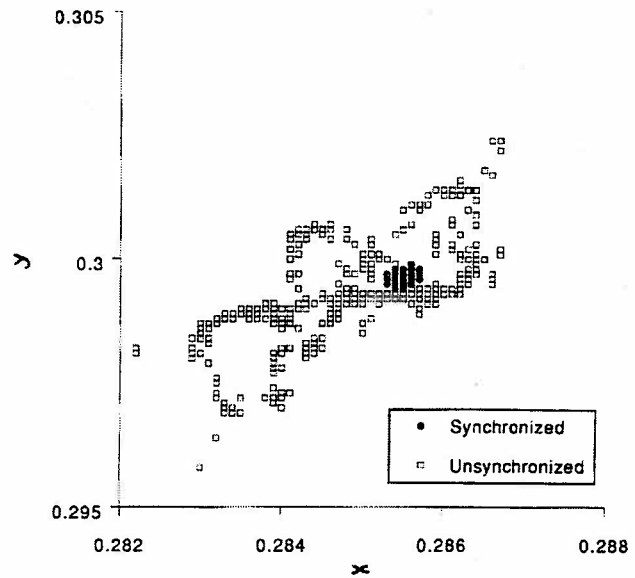


Fig. 4.3: Effect of synchronising measurement period to that of display

4.2.2.2 Dynamic range

In a conventional spectroradiometer the dynamic range can be extended by gain changes in the post-detector amplifier on a wavelength by wavelength basis. With the diode array instrument any range adaption mechanisms (exposure-time, entrance pupil iris, neutral density filter turret) apply equal adaption at all wavelengths.

The diode array type of instrument tends towards a smaller dynamic range between the spectral peaks and the noise floor, (though some instruments are capable of a dynamic range of 32,000 : 1).

4.2.2.3 Stray light

In applications where monochromator stray light is a limiting parameter the conventional spectroradiometer can use a double-monochromator. This option is not available on the diode-array configuration.

If an operating wavelength range in excess of 2:1 is desired then filters to suppress second-order responses can be placed over some parts of the diode array.

4.2.2.4 Uniformity across the measuring field

The area of the item under test, within the measuring field, is wavelength dispersed and imaged on to the detector array.

Thus any small monochromatic point of light within the measuring field is imaged on to a different part of the array dependent upon where the point is within the field.

Movement of the point in one axis will cause the image to fall on different array elements and hence record different wavelengths.

Movement of the point in the other axis will explore any non-uniformity of response within one array element. The instrument should be calibrated with a source which uniformly fills the measuring field in order that the errors described above average out to yield consistent and accurate readings.

However, if the display under test has a spatial structure within the measuring field there is an opportunity for complex error patterns. The propensity to such errors has to be evaluated for each application.

It is proper practice to uniformly fill the detector, but this is not always possible due to the spatial structure of the source.

Spatial 'scramblers' are often used to eradicate the above problem. Refer to section 4.1.4 for further information.

4.2.3 Calibration of Diode Array instruments

A silicon detector is a more stable device and needs less regular calibration checks than a PMT. However the user may wish to change acceptance aperture (angle), input slit to the spectrometer head or even the whole receptor, in which case the instrument will need to be recalibrated for these new configurations.

To make this calibration a first scan is made against a mercury light source, the emission lines of which are used to check the wavelength calibration, and if necessary, provide a correction factor. Following this, a second scan is made against a reference light source to give a spectral power calibration. The calibration of this reference light source itself is normally traceable to a National Standard. Excluding lamp warm up time the whole procedure can be carried out within a few minutes.

4.2.4 Conclusion

Some of the potential drawbacks of the diode-array type instrument have been outlined. The significance of these has to be evaluated for each application and weighed against other issues such as cost, bulk, flexibility of application, speed and ease of use.

Any comparison of the various types of spectroradiometer will not show a "best", but will indicate which is most appropriate for a specific application.

5 COLORIMETERS

Colorimeters are the most commonly used devices in the measurement of the colour of visual displays. They are simple and portable, but lack the versatility and accuracy of the spectroradiometer.

5.1 GENERAL

Colorimeters are the simplest form of colour measurement apparatus. With respect to light collection, they come in two general types. The first uses an eyepiece aperture approach similar to that of a spectroradiometer enabling the user to view the area being measured. Such devices will usually require tripod mounting. The area measured on the display can be varied either by selecting from a range of apertures, or by changing the display to colorimeter distance. The second type uses the direct contact approach whereby the measuring head is placed on the surface of the display, often held by a suction cup. This arrangement will exclude ambient light, the measurement area is fixed, and usually quite large (typically 30 mm diameter).

Colorimeter design uses the idea that any colour may be uniquely described using only three numbers. The instrument contains either three detectors, each with a filter to make them sensitive to blue, green and red respectively or a single detector with the filters mounted in a filter wheel. In a reasonable quality instrument these will closely match the CIE colour matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$. The lobe of $\bar{x}(\lambda)$ in the blue is sometimes given by a fourth channel but more likely to be an arithmetic derivation of the detector used for $\bar{z}(\lambda)$. As with the human eye these filters have a broad response.

See Chapter 3 for a description of the CIE colour specification system.

5.2 APPLICATION

Provided that constant calibration and measuring geometry are maintained, it is possible to divide measurement problems into two main types; those associated with spectral distribution of the radiance of the display and those associated with the selected measurement area.

5.2.1 Spectral Distribution

Colorimeters would produce comparatively good measurements if a display were a spectrally flat reflector illuminated by tungsten or other light source with a continuous broad spectral output. However the majority of displays are:-

- Cathode Ray Tubes where phosphors exhibit narrow energy "spikes".
- Liquid Crystal Displays where fluorescent backlights may be used which again can generate narrow, high energy "spikes" .
- Light Emitting Diodes which in themselves have narrow band emissions.

Spectral filters which exactly match the CIE functions have yet to be manufactured, and the magnitude of the mismatch errors varies instrument to instrument. The error versus wavelength functions of the filters are designed such that with typical continuum spectra the errors average out to a low value. However, with a line spectrum test subject no such averaging occurs and significantly larger errors in colour measurement can arise. Note that even colorimeters of the same model can give different measurement results because of variations in filters and detectors, filter ageing and electronic factors. Figure 5.1 shows how the values of colours on a CRT measured using a spectroradiometer (marked with diamonds) compare with the results from a colorimeter (the point at the end of each line originating from a diamond). The resultant vectors have been multiplied by a factor of ten to make them more visible. Sets of results from two instruments of the same model are shown, both instruments were adjusted to agree with the spectroradiometer for a white of maximum luminance. Although they are identical models they have different systematic errors.

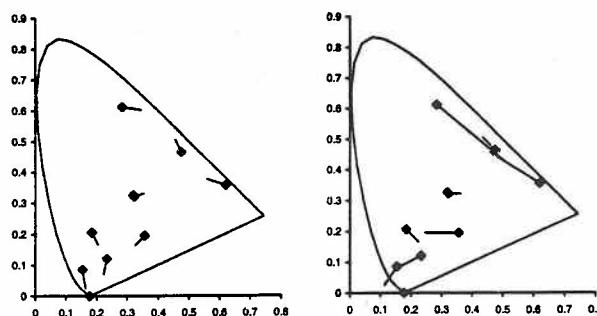


Figure 5.1: Systematic errors of two colorimeters

A badly designed colorimeter may be sensitive to UV or IR radiation leading to significant errors because these invisible radiations will be incorrectly recorded as visible radiation.

As with the diode array spectroradiometer, the analogue to digital converter in a colorimeter has a sampling period which can 'beat' with the display period. Similar results to those in Figure 4.3 have been found with colorimeters. Some colorimeters can be synchronised to the refresh rate of a display to reduce error.

5.5.2 Measured Area

The best way of measuring a CRT with a tristimulus colorimeter is to look at an area which contains a large number of pixels. This ensures that, within experimental error, there are always the same number of pixels of each colour within the measurement area. If it is necessary to look at a smaller area great care must be taken when aligning the instrument to ensure that equal areas of each colour fall within the measurement area.

Different colorimeters use different methods of light collection. With some, light from the display is conveyed down a fibre optic bundle to the three (or four) detectors. The choice of which detector an individual fibre delivers light to bears a completely random relationship with the position on the display - therefore in effect the detector head can be thought of as an array of many 'micro-detectors'. A second approach is to have the three detectors looking at the same area using a beam splitter system. A third method has the detectors looking at a diffuser placed on top of the display. This method can lead to measurement errors as light may not fall evenly on all three detectors due to spatial non uniformity on a CRT. The scale of this error can be investigated by repeating a measurement with the colorimeter rotated by 180°.

5.5.3 Conclusion

The value of colorimeters lies not in their accuracy over wide colour ranges, but in their stability and portability. They are very useful for examining small colour differences on a display, or for checking a display's stability. If the user can be assured that nothing changes in the light generating part of the display, a simple Tristimulus Colorimeter can be used to compare the sample display against a known calibrated display, so long as the calibrated display has an identical spectral power distribution. Depending on the particular instrument used this can either be done by using the instrument readings as arbitrary parameters or by using it in "colour difference" mode where the instrument stores the results from a calibrated display and presents the divergence.

5.3 TELEVISION COLOUR ANALYSERS

Ensuring a high standard of picture quality has become even more important with the increasing interchange of programme material from different sources such as TV studios and production houses. TV Colour Analysers can assist the TV engineer in this process by meeting the demand for easy control and adjustment of the white reference of any monitor, and it is this specific application orientated design that differentiates them from general purpose filter colorimeters.

TV analysers consist of a measuring head that is placed on the CRT and a hand held display unit. The detection system is essentially a colorimeter, though the detectors do not necessarily match the CIE colour matching functions. A fourth photodetector, if present, is used to synchronise the instrument to television field frequency to overcome the problem of beat frequencies with the analogue to digital converters within the analyser. A low pass filter

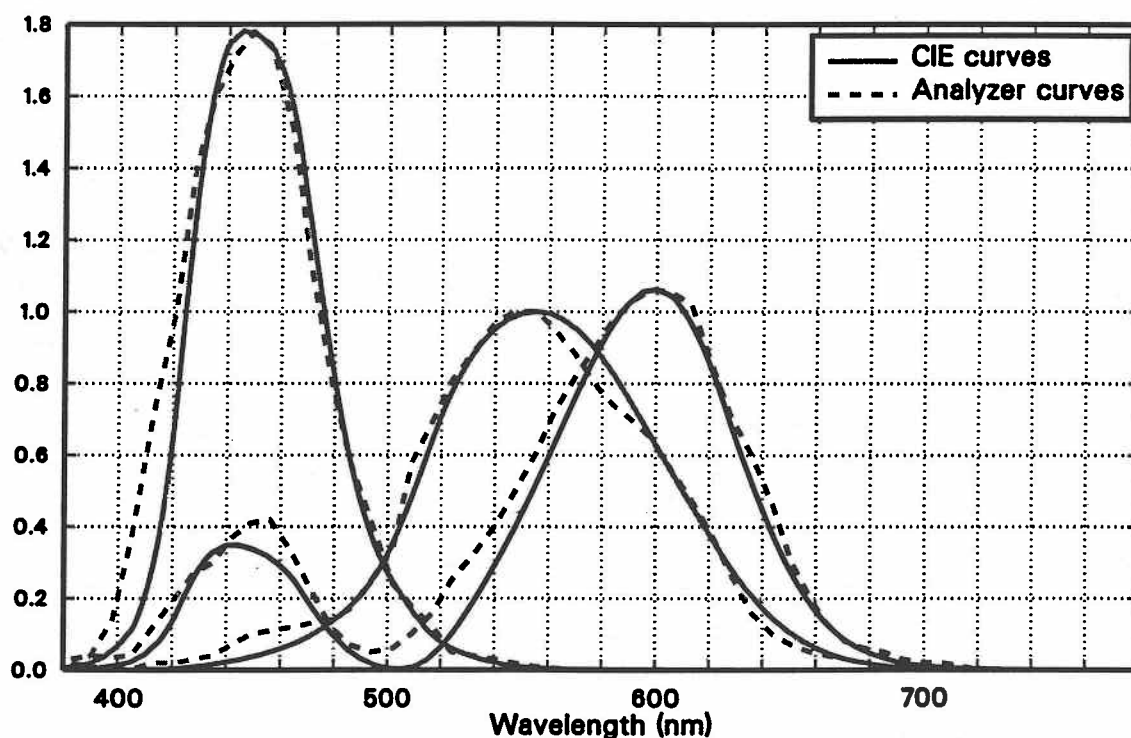


Figure 5.2: Spectral responsivities of the three channels of a TV colour analyser.

circuit in the analyser is a more widely used alternative.

Typical spectral responsivities of the three main detectors are shown in Figure 5.2. These curves indicate the problems that will arise with some measurements. For example, displays with spectral power distributions which have significant power in the regions of the spectrum where the response of the analyser differs from the CIE spectral tristimulus values, will require correction. For accurate analyser results, tabular data of both typical spectral power distributions of the display and the spectral responsivities of the three channels of the analyser are required.

The spectral responsivities of the channels of analysers may be measured using an abridged monochromator system consisting of a tungsten halogen lamp and narrow bandwidth interference filters which will have been calibrated against a standard photodetector (of known spectral responsivity). The analyser should be uniformly illuminated and sufficiently close wavelength intervals used to generate curves as shown in Figure 5.2.

Manufacturers of TV analysers will probably have television monitors with either the EBU or SMPTE 'C' phosphors calibrated by spectroradiometry at a national standards institute. The calibration of reference grade TV analysers will be checked at the institute against the monitor and again on return to the industrial standards test laboratory.

These instruments work very well for direct view CRTs with standard phosphor sets, but for displays with unusual phosphors such as projection CRTs or LCDs it would be wise to discuss the specific measurement requirement with the manufacturer.

The instruments work in either of two modes, xyY and RGB. In the xyY mode the results can be expressed in either xyY, u'v'Y or CIE $L^*u^*v^*$. The RGB mode is designed for the TV engineer who needs to set the red, green and blue guns of the CRT to achieve the desired white reference. For this application, the design of the analyser readout is important to make the instrument easy to use. Some instruments use three analogue bars, representing red, green and blue, which can be brought to a reference mark on the analyser display by adjusting the monitor, enabling the correct setting of the monitor to be achieved.

As the CIE spectral tristimulus curves overlap, there will be a crosstalk between the red, green and blue readings in the RGB mode. Some analysers can store the characteristics of the phosphors in their memory allowing calculations to be made so that crosstalk in the displayed values of R, G and B is minimised. Various white references can also be stored in the instrument.

6 CONSIDERATIONS FOR COLOUR MEASUREMENT

This Chapter contains information on instrumental and measurement techniques

6.1 GEOMETRY

In most circumstances practical issues dictate the use of the "spot-meter" type of light collecting geometry. That is the item under test is imaged by a lens on a field stop and the photo-sensor is placed behind a field stop. The reasons for this are:-

- a) It is usually necessary to measure the emission from a specific well-defined area of the display.
The display image plane is rarely accessible for direct masking - in directly viewed displays the image plane is several millimetres behind the front glass and for a Head Up Display will be an aerial image at near infinite distance.
- b) It is desired to measure display emission at specific viewing angles. This will be appropriate where display technology gives rise to strong angle-of-view dependence such as LCD panels or any display involving interference filters.
- c) In any situation where the colour measurement equipment must be remote so as not to obstruct visual or hand access. Often it is necessary to mask off areas which are not to be measured.

When "spot-meter" type optics are used there must be means of aiming the spot at the desired part of the display. Some instruments are fitted with an aperture mirror system which superimposes an aiming graticule on an image of the display under test. This permits the user to see exactly which area is being measured.

6.2 CONSIDERATIONS RELATING TO THE SPATIAL PROPERTIES OF DISPLAYS

6.2.1 Variability with position

Most display technologies exhibit unwanted but significant variation of emission with position on the display surface. This has little impact on colorimetric techniques except for a need to define and locate the area being measured and it is likely that more measurement will be needed to characterise a display.

6.2.2 Display fine structure

Most display technologies comprise a regular fine structure of light emitting pixels. These technologies include Shadow-Mask CRTs, Beam-Index CRTs, Matrix LCDs and Matrix LEDs. There are wide variations in the pattern and pitch of the structures so generalised recommendations are not possible but the colorimetrist should be aware of potential pitfalls.

It is usually assumed that the structure pitch is fine enough to yield colour-fusion in the users visual system so instruments should respond to the spatial average colour properties. Three

types of measurement problem can be encountered:-

a) *Measurement field size too small*

If the measuring field is smaller than several multiples of the structure pitch there will be colour errors manifested as variations of colour reading with only small changes in placement of the measuring field with respect to the structure. Small changes here means of the order of half the structure pitch. The magnitude of potential errors can readily be estimated from the geometry of the display structure.

b) *Measurement field size too large*

Any spot-meter type of instrument will be calibrated on the assumption that the measuring field is over-filled by the light emitting surface.

When attempting to measure colour properties of small details in displays serious errors may arise from under-filling the field. This is where the "aperture-mirror" approach to viewing optics is invaluable.

It is not recommended that correction factors are calculated for known under-filling.

c) *Instrument response non-uniformity*

Most instruments of the spot-meter type exhibit a degree of non-uniformity of response across the measuring field. Instrument calibration makes the assumption that the measuring field is uniformly filled by the item under test.

In some types of instrument, for example, a straight forward spot-photometer, the uniformity should be good.

On the other hand there are other types of instrument in which non-uniformity is an inescapable consequence of the instrument design configuration. Examples of this are:-

- The tristimulus colorimeter using a tri-furcated fibre-optic bundle to convey flux from the field-stop to the three channels.
- The diode-array type of spectroradiometer.

It is clear that a combination of a display with fine-structure and an instrument response with fine structure can yield some complex interactions. Each situation needs to be examined separately, and is amenable to first-order prediction the size of error should be possible provided one can obtain an adequate description of the instrument configuration.

6.2.3 Display viewing angle variations

Some display technologies will exhibit strong variation of colour properties with viewing angle and may need therefore to be characterised as a function of viewing angle. Examples of such displays include:-

- Any display using interference filters
- LCD displays
- LED displays

○ Projected image displays such as HUDs

As well as the need to make additional measurements, the numerical aperture for the light-collecting optics must be carefully chosen. Obviously a high Numerical Aperture, (NA), is desirable to collect maximum flux and avoid signal/noise limitations.

However, we have to bear in mind:-

- a) High NA implies small depth of focus.
- b) High NA implies a measurement over a range of angles around the intended measurement angle and therefore gives rise to measurement errors - particularly when measuring LCDs.
- c) A projected image display may be able to fill the users eye-pupil under a given condition but not be able to fill the pupil of a high NA instrument resulting in instrument readings which are not representative of what the intended user of the display will see.

The measurement result may only be valid for the particular NA used for the test.

6.3 CONSIDERATIONS RELATING TO THE TEMPORAL PROPERTIES OF DISPLAYS

Colorimetry was originally developed to measure the colour of reflecting surfaces whose reflectance properties are not time dependent (at least not over the time duration of a measurement).

However, many display devices emit their light in short sharp pulses. The Talbot-Plateau law (Talbot, 1834), is usually invoked which says that the visual response is mediated by the temporal average of the light, provided that the pulse rate is high enough not to evoke a perception of flashing. Therefore colour measuring instruments need to respond strictly to temporal average (excluding those situations where a display is deliberately "flashed" at say 2 Hz as an attention-getting feature).

Fortunately most instrument designs naturally give time averaged results but there are pitfalls for the unwary. First let us consider the temporal characteristics that might be encountered. A phosphor element on a CRT display being scanned with a 25/50 Hz interlaced raster will receive an excitation pulse about 100 ns wide every 40 ms. The phosphor decay characterisation will broaden the pulse to perhaps 40 μ s for a blue phosphor and up to 10 ms for a green phosphor. Thus we could encounter temporal waveforms exhibiting peak:mean ratio up to 1000:1.

The measurement problems that might occur are:-

- a) The detector of the instrument (say a photomultiplier) may have fast response and reproduce the pulsed-light waveform. However, the following electronic amplification may severely overload on the pulse peaks (although it can handle then mean level) so that subsequent extraction of the temporal average is in error.
- b) The red, green and blue components of a display will usually have different temporal parameters.

- c) Some instruments (for example the diode array type of spectroradiometer) extract the temporal average by integrating the light signal over a known period of time.

Very bright displays are often measured using a short integration time and this can cause errors to occur. If for example the display is refreshed at 20 ms intervals and the instrument integrates over say 70 ms the integration will sometimes capture 3 pulses and will sometimes 4 pulses, resulting in $\pm 14\%$ variability in reading.

Two possible remedies in this situation are:-

- Attenuate the light reaching the instrument with a neutral density filter to allow longer integration periods to be used.
- Ensure that the integration period is exactly an integer-multiple of the display refresh period.

7 MEASUREMENT UNCERTAINTIES, ERRORS AND CORRECTIONS

A value from a measurement is of limited value unless it is quoted with a figure of uncertainty. This requires an assessment of the measuring system's errors. This chapter looks into estimating errors and how to draw up an uncertainty budget.

7.1 INTRODUCTION

7.1.1 Measurement uncertainties - defining terms

Before embarking on a full description of sources of uncertainty and how to deal with them, it is worth defining several important terms:

7.1.1.1 True value, errors and uncertainties

The aim of any measurement is to find the best estimate of the true value of a quantity being measured. True value is an ideal concept. In some cases a conventional true value is used. Examples of conventional true values are the value assigned to a reference standard or the value measured with a reference instrument.

The result of a measurement will generally differ from the true value. The difference is called the error. Following correction for all known errors, the magnitude and sign of the residual error is unknown, so the concept of uncertainty is used. The uncertainty of a measurement is an estimate of the range of values within which the true value is thought to lie.

7.1.1.2 Random and systematic errors

Random errors take a different value when the measurement is repeated for a given set of conditions. The uncertainty due to random errors can be described by the standard deviation.

If the parameter x being measured has a value x_1 for one measurement, x_2 for the next, etc., then plotting a histogram of the number of times x_1 etc. is read against x usually produces a curve similar to that which is expressed by a Gaussian equation

$$y = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(x - \bar{x})^2}{2\sigma^2}\right]$$

The following parameters are defined (Campion 1973) :-

mean $\bar{x} = \frac{\sum x_i}{n}$

where there are n values of x .

The standard deviation σ is

$$\sigma^2 = \frac{\sum_{i=1}^n (x_i - \bar{x})^2}{(n - 1)}$$

$$= \frac{(\sum x_i^2) - n(\bar{x})^2}{(n - 1)} .$$

The standard error of the mean is

$$SEM = \frac{\sigma}{\sqrt{n}} .$$

It is clear that the SEM will become smaller as the number of measurements increases. The square of the standard deviation is called the variance.

Systematic errors have the same value each time the measurement is repeated using a particular instrument and set of conditions. Nevertheless, it is recommended that the estimated uncertainty is described in terms of a corresponding standard deviation. The estimation of the size of this error is based on experience or other information.

Random errors in one situation can become systematic in another. For example, an instrument used to perform a calibration at a primary calibration laboratory will have a random uncertainty. This random error will become systematic (with the same numerical value of uncertainty) when a secondary laboratory uses the measured value as a reference for subsequent measurements. Even within one laboratory, errors which are systematic over a short period of time may become random over a longer period.

7.1.1.3 Combining uncertainties

There are often several sources of uncertainty within a measurement which can be found separately and combined within an uncertainty budget to provide an overall standard deviation. The recommended method of combining component standard deviations is to use the 'root-sum-square' method:

$$\text{Total uncertainty} = \sqrt{(\text{Sum of each (uncertainty)}^2)}$$

7.1.1.4 Accuracy and precision

Accuracy describes the closeness of agreement between the measurement result and the (conventional) true value. This includes uncertainties due to both random and systematic errors.

The term precision gives the closeness of agreement between repeated results for the same conditions - therefore including only uncertainties due to random errors.

7.1.1.5 Repeatability and reproducibility

Repeatability describes the random uncertainty of measurements under the following conditions - the same: measurement method; observer; measuring instrument; location; conditions of use.

Reproducibility describes the random uncertainty when any of the above conditions are changed. Therefore it must always be qualified to indicate which conditions are changed.

7.1.1.6 Expression of uncertainty

It is normal to multiply the standard deviation by a coverage factor k , to give a range within

which the true value will lie with a greater level of confidence.

For results that have a Gaussian distribution $\bar{x} - \sigma$ to $\bar{x} + \sigma$ ($k=1$) covers 68% of the total area under the curve which means there is a 68% chance that any measurement will fall between $\bar{x} - \sigma$ and $\bar{x} + \sigma$. 95% of the area is covered by $\bar{x} \pm 2\sigma$ and 99.7% by $\bar{x} \pm 3\sigma$. Thus any repeated measurement will lie within $\bar{x} \pm 3\sigma$ for 99.7% of the time or number of readings. The policy at NPL is to state uncertainty at $\pm 2\sigma$ or 95% confidence level (leaving a 1 in 20 chance that a measurement may be outside the range). For a broad range of practical measurement situations a factor of a factor of $k=2$ is applicable and the overall quoted uncertainty will be $\pm 2\sigma$.

7.1.2 Sources of uncertainty

The comments in this section relate only to an electronic light measuring device in general. For more specific sources of uncertainty relating to specific display and detector types, consult the preceding chapters.

7.2 RANDOM UNCERTAINTIES

Measurements are subject to noise originating from the measuring electronics and detector. Good instruments are designed to minimise this noise and therefore the dominant source of noise is from the measurement technique.

7.3 RANDOM UNCERTAINTIES IN MEASUREMENTS

Normally a quantity cannot be obtained from the measurement of only one parameter such as the beam intensity. Luminance, for example, is derived from three flux readings, each of which has its own uncertainty; Y_s and σ_s , the signal and its uncertainty measured when the incident beam from the sample display falls on the detector, Y_r and σ_r from a standard reference lamp, and Y_d and σ_d measured when there is no radiation (dark reading). The dark reading represents any steady signal produced by the electronics and/or the detector in the absence of radiation, and is assumed to apply to all readings. If Y_k is the known true luminance of the reference lamp then the measured luminance of the display will be:

$$L = \frac{Y_s - Y_d}{Y_r - Y_d} \times Y_k$$

If two parameters are added or subtracted the squares of the uncertainties are added, ie if $A = B + C$ then $\sigma_A^2 = \sigma_B^2 + \sigma_C^2$. If they are multiplied or divided, the fractional values are squared and added ie if $D^2 = E^2 + F^2$ then

$$\frac{\sigma_D^2}{D^2} = \frac{\sigma_E^2}{E^2} + \frac{\sigma_F^2}{F^2}$$

$$\text{Thus } \frac{\sigma_L^2}{L^2} = \frac{\sigma_s^2 + \sigma_d^2}{(S_t - S_d)^2} + \frac{\sigma_r^2 + \sigma_d^2}{(S_o - S_d)^2} + \frac{\sigma_{Y_k}^2}{Y_k^2}$$

7.4 RANDOM UNCERTAINTIES BASED ON REPEATABILITY

It is not possible to determine the random uncertainty of a luminance measurement from a single value. It is necessary to make many measurements to obtain the mean and standard

deviation. For example, when the NPL Reference Spectroradiometer is used for calibration work the samples are measured several times, preferably on different days, and the SEM is based on these.

The standard deviation (σ) of the mean value of a series of readings is usually greater than the standard deviation of the individual values based on noise alone. This is because the samples are spatially non-uniform and there are usually slight variations when attempting to re-create a measurement geometry. This may be incorporated into an assessment of sample noise and it is usually the main source of uncertainty in high accuracy measurements.

7.5 SYSTEMATIC ERRORS

There are systematic errors associated with most measurements. Most parameters or properties, for example, have a temperature coefficient. If measurements are made at temperatures other than the specified one then an error is introduced. This can be measured and corrections applied. The correction will have an associated uncertainty which has to be included when calculating the overall uncertainty.

With radiance and reflectance measurements errors come from detector non-linearity, inaccurate wavelength scale, inter-reflections, detector non-uniformity, sphere screening inadequacies and sphere dark sample readings (Clarke, 1986). Wide-band instrumentation such as photometers and tristimulus colorimeters also have an error due to differences between their actual spectral responsivities, and those which they are attempting to emulate - ie CIE functions. These errors and their uncertainties can be measured and when corrections are applied their uncertainties must be included in quadrature as indicated above.

The following points should also be considered when estimating systematic errors:

- Reference sources can 'drift' with time and should themselves be regularly recalibrated. If possible use at least two reference sources to check against each other and stagger their calibration.
- The reference source itself will have an error associated with its value.
- The reference source will rarely be identical to the sample display. So comparisons between reference and display rely on good linearity in the detection system.
- The reference source must be set up exactly as specified by the calibration authority or manufacturer. Look out for factors such as a dusty diffuser.
- Care should be taken in ensuring that the whole of the measuring area of the instrument is filled by the relevant part of the display. Ensure that the collecting optics are accurately focused and aligned.
- Check that ambient light falling on the display is eliminated or closely controlled if it is intended to simulate a working environment. Even someone moving around in a white laboratory coat can effect results.

The assessment of the magnitude of systematic uncertainties must be based mainly on past experience and on a knowledge gained from using different measurement techniques. This is why comparisons of measurements between laboratories are so valuable. The different

methods used in the various laboratories can bring previously overlooked systematic errors to light and thus improve measurement techniques for the future.

By their very nature, systematic uncertainties are difficult to treat statistically. It is not possible to calculate confidence limits directly, but instead they must be estimated. There is no definite rule as to how this should be done, although various methods have been proposed.

Systematic errors are normally assessed as being between two values, for example the stray light in a monochromator may be assessed to be no greater than 5% of the measured signal - ie the measured signal lies in the range 0% to 5%. The best correction for this systematic error would therefore be 2.5%. In this case but this would be uncertain to $\pm 2.5\%$.

7.6 UNKNOWN SYSTEMATIC ERRORS

There is always the possibility that there are systematic errors of unknown cause. One way of estimating these is to measure the same sample on different instruments using different techniques. There are very few reference instruments in the world and one purpose of international inter-comparisons is to identify possible systematic errors. Where this is not possible an estimate has to be made based on a knowledge of instruments and the materials being measured.

Systematic error estimates from unknown causes are also included in the uncertainty by adding in quadrature as indicated above.

7.7 SPECTRAL RADIANCE SCALE

A spectral radiance scale is maintained in the UK at the National Physical Laboratory using the NPL Reference Spectroradiometer. This contains a double monochromator, and uses the continuous scanning technique. A linear transducer attached to the sine drive of the grating assembly gives a wavelength measurement to 0.01 nm. The detector signal and a stable reference signal are continuously integrated, using voltage to frequency converters and counters over a series of contiguous wavebands 0.2 nm wide. Fluctuations in the source are corrected for using a separate broadband detector placed next to the source. The reference signal is used to correct for changes in the scan speed - the final reading for each band is found by dividing the signal count by the reference count, then subtracting a dark current reading. The integration process ensures that no part of the spectrum is omitted or measured twice.

7.8 TRANSMITTANCE AND REFLECTANCE SCALES

NPL's Reference Spectrophotometer is used annually to determine the UK's transmittance scale at a series of wavelengths. The scale is held on a series of metal-on-silica filters and is transferred to the high quality commercial instruments which are used to calibrate customers' standards. The uncertainties are thus those calculated from measurements on the reference instrument summed in quadrature with those from the commercial instrument.

In order to estimate unknown systematic errors and to ensure international acceptability, inter-comparisons are made with other national laboratories, eg NIST (USA), and PTB (Germany) (Eckerle 1990). These intercomparisons show differences larger than the uncertainties quoted by each laboratory because of imperfections in the filters used for the

comparisons, such as spatial non-uniformity, ageing and diffuse transmittance, and secondly, the different test methods of the participants. The uncertainty quoted for NPL's final values is increased to include the differences so that a filter measured at NPL will have the same transmittance as it would have if measured at NIST or PTB within the combined uncertainties.

The scale of diffuse reflectance is based on an international mean. Absolute diffuse reflectance is a difficult parameter to measure and this partially accounts for the larger uncertainties associated with diffuse reflectance measurements than transmittance measurement.

7.9 USERS' ACCURACY

When a user calibrates an instrument, instrumental values have to be corrected. The difference between the calibrated values and the measured value is the correction. The instrument uncertainty (preferably the standard deviation obtained by repeated measurements as indicated above) then has to be added in quadrature to the standard's calibration accuracy to produce the accuracy of calibration of the instrument.

8 TRACEABILITY TO NATIONAL STANDARDS

The National Measurement System of DTI links measurement scales together within the UK. Without such a system there would be disagreement between instruments. The system is maintained by the National Physical Laboratory who also realise the reference scales at the highest possible accuracy levels - calibrated artefacts carry scales from an accurate instrument to a less accurate one, but at each stage in a calibration chain uncertainty increases.

8.1 THE NATIONAL MEASUREMENT SYSTEM (NMS)

The NMS is a mechanism through which measurement scales are harmonised throughout the UK. It ensures that a bolt made in Cornwall will fit a nut manufactured in Strathclyde since the scales of the length measuring equipment used in each case are related to a common scale. At the top of the NMS is the NPL which is responsible for maintaining and disseminating physical scales such as length, time, temperature and spectral radiance using primary standards and scales. The UK's NMS is harmonised with that of other countries around the world via intercomparison, so that goods can be traded on an international basis.

8.2 MAINTENANCE OF PRIMARY SCALES RELATED TO COLORIMETRY OF VISUAL DISPLAYS

8.2.1 Spectroradiometric Scale

The spectroradiometric scale is ultimately traceable to a primary standard cryogenic radiometer. This instrument is an electrically calibrated absolute radiometer in which the heating effect of absorbed radiant power is determined by substitution with an equivalent amount of electrical power. A temperature sensor is used to establish equality between radiant and electrical heating. The cryogenic radiometer operates at liquid helium temperatures and has a measurement uncertainty of 5 parts in 10^5 , a significant improvement in uncertainty over earlier room temperature radiometers. It provides an absolute radiometric scale at the wavelength of suitable intensity stabilised laser lines. These lasers may then be used to calibrate transfer standards in the form of detectors, which in turn are used to calibrate the output of lamps.

Members of the industrial and scientific community can take traceability from NPL spectroradiometric and luminance scales using transfer standards (lamps or detectors), or by having a sample of their own product calibrated. This calibrated artefact can then be used to calibrate their own equipment.

8.2.2 Reflectance and Transmittance Scales

These scales are relevant to the characteristics of display components and LCDs. Reflectance and transmittance scales are not SI based, but are ratio measurements. National standards for reflectance and transmittance are determined at NPL using the Reference Spectrophotometer and the Reference Reflectometer. The performance of these instruments is very accurately known and they are checked against similar instruments throughout the world to achieve international compatibility in measurement.

8.2.3 Colour

Colour may be seen as a quantity derived from spectral power distributions of a source, and as such, colour scales are direct transformations - using CIE functions - of spectral data, be it radiance or reflectance. The colour of luminous or reflective media can be related to the national standard by tracing their spectral power distribution, or spectral reflectance with illuminant to the appropriate scale and applying the standard CIE calculation. The CIE publishes the arrays of colour matching functions and illuminants on computer disc for those who wish to perform their own colorimetric calculations. In the UK the disc is available from CIBSE.

8.3 NATIONAL FACILITY FOR THE MEASUREMENT OF COLOUR OF DISPLAYS

NPL has designed and built a facility for the measurement of the colour and luminance of displays. This facility compares the spectral radiance of customers' displays with that of an NPL in-house standard lamp. The comparison can then be used to calculate the spectral radiance of the display:

$$D_a(\lambda) = S_a(\lambda) * \frac{D_m(\lambda)}{S_m(\lambda)}$$

Where

$D_a(\lambda)$ = true spectral radiance of display

$S_a(\lambda)$ = true spectral radiance of standard lamp

$D_m(\lambda)$ = measured spectral radiance of display

$S_m(\lambda)$ = measured spectral radiance of standard lamp

Using the standard set of CIE equations this spectral radiance data can be transformed to CIE chromaticity coordinates.

There are two instruments used at NPL to provide traceable spectroradiometric and colorimetric measurement of displays. One is a telespectroradiometer scanning at 5 nm intervals. The instrument has a single monochromator with order sorting filters. The detector is a photomultiplier tube. The current from the tube is converted to voltage and time-smoothed using a low pass filter. The voltage is read by a digital voltmeter. The voltmeter, filter wheel motor and grating drive are controlled by a computer which also performs colorimetric calculations. An in-house transfer standard lamp is measured at the start and end of session so the instrument is effectively calibrated every time it is used. The second instrument used for measurement of displays is a diode array telespectroradiometer. This is slightly less accurate than the former instrument but is highly portable. It is regularly calibrated using an in-house standard lamp.

Laboratories with their own spectroradiometers can obtain calibrated lamps from NPL to calibrate their own instruments.

Most types of display are unstable and are affected by electro-magnetic fields and physical shock. When the colour of a display is calibrated at NPL, (obtaining values $NPL[x,y,Y]$), the recommendation is to take an additional measurement of the calibrated area on the display using a tristimulus colorimeter, ($C[x,y,Y]$). Note that due to systematic errors within the colorimeter, $C[x,y,Y]$ will probably not be identical to $NPL[x,y,Y]$. When the display is returned to the customers' laboratory, its calibration may have drifted during transit but can

be reset to show the 'certified colours' by tweaking the gun voltages until the colorimeter gives $C[x,y,Y]$, inferring that the display is showing $NPL[x,y,Y]$. Note that the use of colorimeters for this high accuracy purpose relies on the fact that the generation of a particular colour on a CRT has a unique solution (depending on specific proportions of the red, green and blue primaries), it would not be valid for the colorimeter to be used to measure the colours of another display which uses different primaries.

It is also possible to characterise detector performance at NPL. A regularly used service characterises the performance of tristimulus colorimeters by comparing the colour of a display as measured using the spectroradiometer with the results of similar measurements using the colorimeter. A look-up table converting colorimeter values to traceable values can be established using the results. Note that the table is only true for the particular display being measured as the systematic errors of the colorimeter depend on the spectral power distribution of the display, (see Chapter 5 for details).

APPENDIX A: GLOSSARY

Within this document the following terms have been used to denote the following meanings.

Calibration

This is the process of ensuring that the measuring instruments being used are giving the correct answers. (By adjustment of the instruments and/or by establishing declared correction factors).

The process is carried out by a Calibration and Standards Department who are also responsible for traceability to international standards.

(Perhaps there would be less confusion if we termed this "Instrument Calibration").

Characterisation

This is the process of establishing by measurements the actual colorimetric parameters of a particular display sample.

The purposes are various and could include:-

- Assessing the performance of a candidate display or display component.
- Proving the performance of a prototype display product.
- Establishing the objective parameters of a display that is being used for subjective experiments. (Which could be termed "Display Calibration")

The activity is carried out by an Engineering Department and requires the use of calibrated instruments.

Product release testing

This is the process of implementing some agreed bench mark tests on display products before delivery to our customer.

This is carried out by an Inspection Department and requires the use of calibrated instruments.

Calibration check

This is an abridged calibration using traceable reference standards but not giving values for all points, rather, it checks that the system is giving reasonable results at a few points.

The value of a calibration check is that it will indicate whether a full calibration is required.

White point

This is the colour of a CRT (or 3 colour display) when all electron guns are set to maximum. There are specifications (EBU, PAL, SMPTE...) as to what this colour should be, typically the colour of standard illuminant D65 - the colour of 'daylight' according to a CIE standard set of data.

Black point

When the guns of a CRT are set to zero, there is usually a residual beam hitting the front faceplate. This means that a colour will be displayed. The intention is often to reduce the luminance of this colour as much as possible, and if it is still evident, to make it as 'neutral' as possible. The author has seen specifications in the past which require the luminance and CIE chromaticities to all be zero. There are two flaws in this requirement - firstly if there were no luminance, it would be impossible to measure colour (a better example phrase would have been "luminance must be below 0.2 cd.m^{-2} "), secondly there is no colour with chromaticities $x=0.000$, $y=0.000$.

Colour temperature

Colour temperature is a one dimensional colour scaling system traditionally used by the lighting industry. It relates the colour of a source to the colour of a black body radiator held at a specified temperature. The equation relating spectral power distribution of a black body radiator to its temperature is Planck's Formula. The curve of points of ascending temperature, plotted on a chromaticity chart is called the Planckian locus. These are the chromaticities of the ideal radiator. When the scale is applied to filament lamps, the spectral profiles are similar to that of the theoretical source. However they are not always exactly the same - possibly due to gas impurities, or filtering by the envelope. The scale is also often used to describe sources which are very different in spectral profile to the Planckian radiator, such as display whites and daylight, and with a chromaticity which does not lie on the Planckian locus.

To solve the problem of describing the colour temperature of sources with chromaticities off the Planckian locus, the concept of a 'correlated colour temperature' (cct) is used. To find the cct of a source, a line is drawn orthogonal to the Planckian locus that passes through the same colour. The cct is given by the intercept of the Planckian locus. For historical reasons, the colour space in which this line is drawn is CIE 1960 CIELuv space, where:

$$\begin{aligned}u' &= u \\v' &= 3v/2\end{aligned}$$

A value of Δ_{uv} can also be given with a cct value to describe the distance between the colour and the Planckian locus.

Some colours - for example blues - cannot be described in terms of a cct since a line drawn orthogonally through the Planckian locus will not pass through their chromaticity coordinates.

APPENDIX B: CURRENT ACTIVITIES IN STANDARDIZATION

Several standards projects currently being pursued by various national and international standard organisations. A brief account of each project is given below,

ISO (International Organization for Standardization)

ISO TC130 (Graphic Technology)

There are two working groups (WG) working in this area, i.e. WG2 (Electronics Data Exchange) is aiming to develop a standard colour image data (SCID) for electronic image evaluation, and WG3 (Process Control) is working to standardise terminology, test procedures, and specification for global colour data exchange within the graphic arts industry.

ISO IEC JTC1 18

WG5 (Text Office Systems Colour Architecture (TOSCA)) is working to provide Colour Data Interchange Transform (CDIT) object framework and to enable the interchange of colour information within an open environment.

ISO 9241 Parts 3, 7 & 8 (Ergonomic requirements for office work with visual display terminals) part 7 reflections, part 8 requirements for displayed colours.

ANSI (American National Standards Institute)

IT8 (*Digital Data exchange standard (DDES)*) is working to develop a colour definition data set and file format that will allow the relationship between the CMYK and the resultant printed colour to be defined, i.e. IT8.7/1 for transmission input and IT8.7/2 for reflection input material.

CGATS (*Committee for Graphic Arts Technologies Standardization*) is working to define colour measurement standards for graphic arts application, and the parameters necessary to characterise a proofing or printing process such as ink colours, substrate, solid ink density, dot gain etc.

CIE (International Committee on Illumination)

A technical committee, TC1-27 (*Colour Fidelity between Reflection Prints and Self-Luminous Displays*) was formed to gather experimental data from available sources for the evaluation of the colour fidelity between a self-luminous display image which is visual and/or instrumental match to a reflection print. The results would be further used to test the predictive performance of various uniform colour spaces and colour appearance models. A model or space will be recommended to assess colour fidelity in industrial practice.

TC2-26, *Measurement of Colour of Self-Luminous Displays*, is working to provide colour measurement standard for measuring display colours using a spectroradiometer.

TC2-21, *Spectroradiometry of flashing lights* includes calibration and use of diode array instruments.

TC2-26, *Guide to characterising the colorimetry of computer controlled displays* includes sections on measuring colours of displays and relating them to National standards. It also contains

a model for converting digital values to displayed colours.

TC2.16, Characterisation for the performance of Tristimulus Colorimeters.

TC2.30, Diode array radiometry.

TC2.34, LED measurement.

Relevant CIE Publications

Subject	Pub No.	Title	Comment
Colorimetry	15.2	Colorimetry 2nd Edition	Contains all recommendations and definitions, related to Chapter 3 of this document
Displays	60	Vision and the VDU workstation	Includes recommendations on how to set up a good working environment for VDU work.
Displays	87	Colorimetry of self luminous displays.	A 40 page bibliography.
Glare	60	Vision and the VDU workstation	
Information systems	39.2	Recommendations for surface colours for visual signalling	
Luminance	69	Methods of characterising illuminance meters and luminance meters: Performance, characteristics and specifications	Includes methods of calibration
Polarization	59	Polarization: Definitions and nomenclature, instrument polarization.	
Spectroradiometry	63	The spectroradiometric measurement of light sources.	
Spectroradiometry	105	Spectroradiometry of pulsed optical radiation sources.	looks at use of diode array detectors
VDU	60	Vision and the VDU workstation	

CIE publications are obtainable from CIBSE in the UK.

EBU (European Broadcasting Union) Publication 3273 - E, October 1993: Obtainable from G.T Waters, Ancienne Route 17A, CH-1218 Grand Saconnex, Geneva, Switzerland.

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