Overview of the Photometric Characterization of Visual Displays

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Abstract

A wide range of measurements may be required in order to fully characterize the properties of a display, but these are generally based on a relatively small number of fundamental measurement parameters: luminance, color, spatial uniformity, angular distribution, reflectance, and temporal characteristics. This chapter provides an overview of the methods and instrumentation used for these underpinning measurements and outlines the major associated sources of potential measurement error and uncertainty.

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List of Abbreviations

BRDF	Bidirectional reflectance distribution function
CIE	Commission Internationale de lÉclairage
CRT	Cathode ray tube display
LCD	Liquid crystal display
LED	Light emitting diode
PC	Personal computer

Introduction

Measurements of the photometric characteristics of displays are important for many reasons, such as assessing performance for product development, manufacture, and quality control purposes, enabling purchasers to compare products on a consistent basis, and as inputs to software used to predict display legibility in specific installations. A range of measurements may be required, as summarized in Table 1. This chapter will provide a brief overview of these measurements, the types of instrumentation that are available, and the major potential sources of measurement error.

Table 1 Measurements for characterizing the optical performance of a visual display

Measurement	Used for
Luminance	Key element for basic specification and comparison of display performance
Color	Key element for basic specification and comparison of color display performance
Gray-level step	Key element for basic specification and comparison of display performance
Contrast ratio	Key element for basic specification and comparison of display performance
Spatial luminance uniformity	Assessing whether luminance variations across the surface of the display will result in unacceptable disturbance to the end user
Spatial color uniformity	Assessing whether luminance variations across the surface of the display will result in unacceptable disturbance to the end user
Angular luminance distribution	Assessing the range of angles over which the display can be viewed
Angular color distribution	Assessing the range of angles over which the display can be viewed
Diffuse reflectance	Assessing legibility of the display under specific ambient illumination conditions
Specular reflectance	Assessing legibility of the display under specific ambient illumination conditions
Angular reflectance	Assessing legibility of the display under specific ambient illumination conditions
Temporal characteristics	Assessing display susceptibility to motion blur for moving images

Luminance

Luminance is the most basic measurement for a display. Not only is it the foundation of many of the other measurements (as detailed in part 51, "Advanced Display Measurement Procedures"), but it is also often used within the display industry as a general rule of thumb regarding the suitability of the display for a particular application. For example, a display with a luminance of 500 cd m^{-2} will be on the borderline of being acceptable ("bright enough") for use in daylight or other high illumination conditions, whereas a luminance of 1,500 cd m^{-2} would be considered to be very likely to be acceptable. Luminance is usually measured for both a black and white screen using a luminance meter (sometimes called a spot photometer) or a telespectroradiometer (see Part 50, "Standard Display Measurement Procedures" and chapter "▶ Standards and Test Patterns" for more details). The measurements are usually performed with the measuring instrument perpendicular to the surface of the display, or at the angle at which the user would normally view the display (if this is not perpendicular to the surface). The size and location on the display of the measured area should be stated, since most displays show some nonuniformity in luminance over the surface. It is also important not to measure too small an area, since this can result in large differences in the measured results with small changes in size or position (at the extreme, if the measurement area is the same size as a single pixel, small movements can mean that the area is either located precisely over a pixel, giving a "high" reading, or only partially over a pixel, giving a "low" reading; neither reading will adequately represent the true display luminance). Precautions must also be taken to minimize the effect of stray light from areas of the screen other than the defined measurement area, and this generally involves the use of either a stray light tube on the measurement instrument or a mask on the surface of the display. Other major sources of error are the performance of the measurement instrument (see Sect. 10, "Mobile Displays, Microdisplays, Projection, and Headworn Displays" and chapter "▶ Measurement Devices") and external influences on the output of the display (e.g., CRTs are susceptible to external magnetic fields and LED displays can be affected by changes in ambient temperature). Results are expressed in terms of candela per meter squared (cd m^{-2}).

Color

The range of colors that can be displayed (the "color gamut") is evaluated by measuring the chromaticities of red (R), green (G), blue (B), and white ($R = G = B$) screens. The approach, precautions, and sources of error are similar to those for measurements of luminance, but in this case, the instrumentation used is a colorimeter (which is typically placed directly on the surface of the screen) or a telespectroradiometer (which is imaged onto the screen and provides measurements of the spectral radiance). Results are expressed in terms of CIE (x,y) or (u',v') chromaticity coordinates or using another specified color system. More details

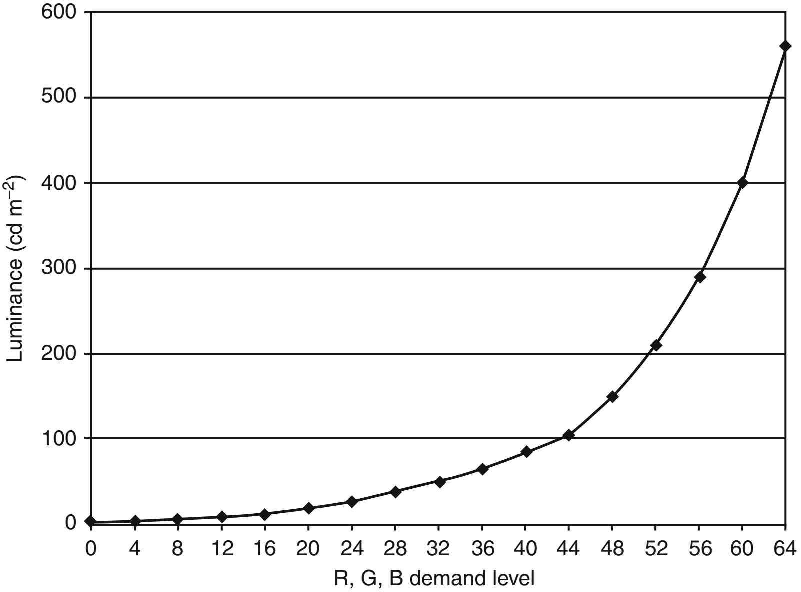

Fig. 1 Example of results from gray-level step measurements

are given in Part 50, "Standard Display Measurement Procedures" and chapter "▶ Measurement Devices."

Gray-Level Step

These measurements are also performed in a similar manner to luminance measurements, but in this case, the white screen is varied over the full range of RGB drive levels (i.e., from 0 to 256), and the luminance is determined for each step (see Parts 50, "Standard Display Measurement Procedures" and 51, "Advanced Display Measurement Procedures"). A test pattern generator is usually used for this purpose (see chapter "▶ Standards and Test Patterns") to avoid problems that may arise if a personal computer (PC) is used to set the gray levels (a PC provides the means for altering brightness, contrast, and gray-level step in a way that is often hidden from the operator). Results are usually expressed graphically, as shown in Fig. 1.

Contrast Ratio

Contrast ratio is defined as the ratio of the highest luminance to the lowest luminance that the display system is capable of producing. The larger the contrast ratio, the greater is the difference between the brightest whites and the darkest blacks that can be displayed. A high contrast ratio is a desirable aspect of any display, but it is not always possible to make a direct comparison between the contrast ratio values provided by different display manufacturers, due to differences in the measurement methodologies used. The most representative measure of contrast ratio for assessing overall display performance is static contrast ratio, which refers to the ratio between the luminances of the brightest white and the darkest black that can be displayed *simultaneously*. Dynamic contrast, on the other hand, refers to the ratio between the deepest blacks and the brightest whites that a display can display, but *not at the same time*, and generally results in higher contrast values. This is particularly true in the case of displays employing backlights (e.g., LCDs), where light can bleed through from the backlight into black areas when an image containing both white and black areas is being viewed (thus reducing contrast ratio), whereas the backlight can be reduced or even turned off if a fully black image is displayed.

A further complication is that, regardless of whether static or dynamic contrast is measured, the results obtained can depend significantly on the ambient lighting conditions. Contrast ratio is often quoted for dark room conditions, that is, with no ambient illumination present and minimal reflections from the surroundings. In most instances, this is not the environment in which displays are used, and different values will be obtained if ambient illumination is present, and/or the surrounding walls, floor, and ceiling can reflect light from the display back onto the screen.

There are two commonly used methods of measuring contrast ratio. The “full on/off” method compares the luminance of a white screen ($R = G = B = \text{max}$) with that of a black screen ($R = G = B = 0$) and has the advantage that it largely cancels out the effect of the external environment (equal proportions of light are reflected from the display to the room and back for both the “black” and “white” measurements, as long as the room stays the same). This method is generally suited only to dynamic contrast measurements, unless it is possible to control the display such that the backlight is fully on even when displaying a black image. The second method is to use a checkerboard pattern, in which the luminance values of all the white squares (or rectangles) are measured and averaged, and similarly the luminance values of the black squares (or rectangles) are measured and averaged. The ratio of the averaged white readings to the averaged black readings is the contrast ratio. This method provides static contrast values. However, accurate measurement of contrast using this checkerboard approach requires the use of a well-controlled dark room, with all walls, floors, ceilings, etc., totally black and nonreflective; this can be difficult and expensive to achieve.

Whatever method is used and regardless of whether static or dynamic contrast is being measured, results are expressed as the ratio between the luminances of the “white” and the “black” conditions, for example, 1,000:1. More details of contrast ratio definitions and measurement methods are given in chapters “▶ Luminance, Contrast Ratio, and Gray Scale” and “▶ Standards and Test Patterns.”

Spatial Luminance and Color Uniformity

The visual appearance and effectiveness of a display can be significantly degraded if there are perceptible variations in the luminance and/or color over the active area of the screen. Such nonuniformities may appear as a gradual variation from one part of the screen to another or as localized variations due, for example, to the structure within the backlight. Prior to the development of imaging photometers/ colorimeters, display nonuniformity was assessed by making measurements at a large number of discrete points across the full area of the screen using a spot photometer, colorimeter, or telespectroradiometer (see chapter "▶ Spatial Effects"). The problem with this approach lies in achieving sufficient spatial resolution and conducting a sufficient number of measurements to characterize fully the performance of the display. In practice, the scientist/engineer performing the measurement generally identifies the brightest and dimmest locations on the display by visual inspection and then performs several measurements around these areas. The nonuniformity can be calculated as a contrast ratio between the areas of highest and lowest luminance. The main problem with this approach is that it does not fully represent the overall nonuniformity of the display but gives only two specific worst case points. The low spatial resolution of the measurements can also mask small area nonuniformities. More recently, therefore, this point-by-point approach to measurements of display nonuniformity has been largely superseded by the use of imaging photometers and colorimeters, which produce two-dimensional maps of the variations in luminance (or chromaticity) over the full screen surface, as illustrated in Fig. 2.

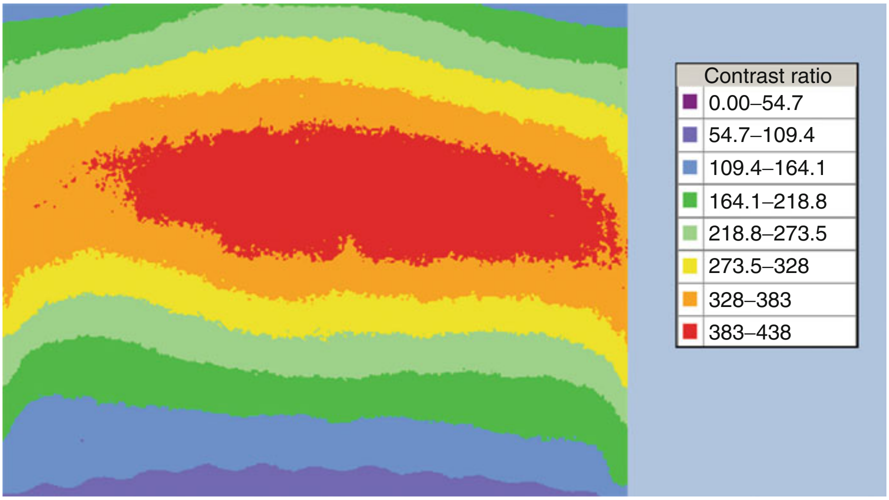

Fig. 2 Example of results from an imaging colorimeter, showing contrast ratio values in false color

Angular Variations in Luminance and Color

Measurements of the angular variation in luminance and color provide the characteristics of the display over the whole forward hemisphere and can be used not only to determine the angular field of view of a display but also to provide a more comprehensive understanding of display legibility under a range of conditions (see chapter "▶ Viewing Angle"). The highest angular resolution and measurement sensitivity is achieved through goniometric methods, in which the luminance or color distribution is mapped as a function of angle. However, these methods require long setup and measurement times and are consequently often too expensive to fulfill the needs of the display industry. Other methods have therefore been developed, based on the use of the latest imaging technologies (Rykowski et al. 2006), but a detailed description of these is beyond the scope of this chapter (see chapter "▶ Measurement Devices" for more information).

Reflectance Measurements

Light reflected from the display surface into the user's line of sight is superimposed on the displayed image and results in a degradation of the legibility of the displayed image. Conventionally, two types of reflection have been considered within the display community: specular reflection and diffuse reflection. However, with the increased use of antiglare and touch screen coatings, a third type of reflection, termed "haze," is now also considered and can be a significant contributor to degraded visual performance.

Diffuse Reflectance

Diffuse reflectance measurements (see chapter "▶ Ambient Light" for more details) are intended to quantify the amount of reflected light that will be superimposed on the displayed image from a uniformly distributed diffuse light source. This diffuse light source provides a reasonable approximation of the illumination environments in which displays are often used. For example, the illumination from the sky is diffuse in nature, so this is an appropriate condition to use for displays used out-of-doors, and although indoor environments generally have a somewhat complicated illumination distribution, even these are often adequately represented by a diffuse source to a first degree (e.g., office lighting is often designed to produce good uniformity across the working plane with no visible "bright spots").

The baseline measurement technique for diffuse reflectance is to place the display inside a large integrating sphere, with a lamp (with baffle) placed behind the display such that this provides diffuse illumination onto the display. Measurements are made of the screen luminance for a measured level of diffuse illuminance and compared with the measured luminance under the same conditions for a calibrated reflectance standard (Kelley 2006). However, this method requires access to an integrating

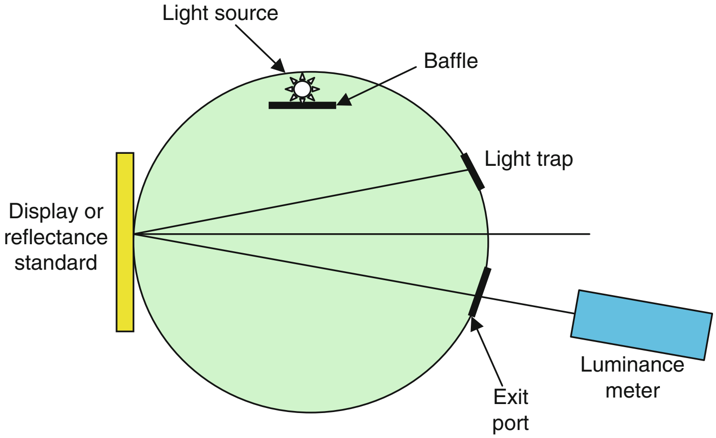

Fig. 3 Schematic of sampling sphere measurement of diffuse reflectance

sphere that is large enough to accommodate the display (the diameter of the sphere should be at least ten times the diagonal of the display), and it is therefore not widely used. An alternative approach is the “sampling sphere method” (Kelley 2006), in which the display is placed against the sample port of an integrating sphere rather than inside it. A lamp is placed inside the sphere, close to the wall, and baffled to prevent direct illumination of the display. The luminance of the display surface is measured using a luminance meter and compared with that measured under identical conditions but with the display replaced by a calibrated diffuse reflectance standard (see Fig. 3). The diffuse reflectance of the display, ρ_{dis}, is given by

$$\rho_{\mathrm{dis}} = \frac{\rho_{\mathrm{std}} L_{\mathrm{dis}}}{L_{\mathrm{std}}}$$

where ρ_{std} is the reflectance of the calibrated standard, L_{dis} is the luminance measured when the display is in position, and L_{std} is the luminance measured with the reflectance standard in position. If the display emits light, then the luminance of the display must be subtracted from the luminance measured under reflection to obtain the net reflected luminance. Measurements are usually made for a range of display conditions (white and black as a minimum) since the reflectance may vary depending on the display settings.

Specular Reflectance

Measurements of specular reflectance are made to determine the degree of “mirror-like” reflection from a display (see chapter “▶ Ambient Light” for further details).

Specular reflections are generally several orders of magnitude larger than diffuse reflections and can be a major source of discomfort if a display is incorrectly positioned within a lit environment. Measurements are usually made by comparing the luminance of display when viewed at angle θ to the normal and illuminated by a point source at $-\theta$ to the normal with that for a calibrated specular reflectance standard (typically a piece of black glass) that is illuminated and viewed under identical conditions.

Angular Reflectance

Measurements of angular reflectance provide the reflectance characteristics of the display over the whole forward hemisphere and can therefore be used to determine the details of how the display reflectance will impact on its legibility under any given conditions (see chapter "▶ Ambient Light" for further details). The importance of these measurements has grown in recent years due to the increasing use of display screens with antiglare or touch screen coatings, both of which introduce nontrivial "haze" reflections, that is, reflections that are intermediate between diffuse and specular in nature. The most serious effect of haze is to "broaden out" the specular reflection, making it less easy for an observer to avoid the reflection by changing their viewing location and thus resulting in a display that is less legible than would be the case if only specular reflection were present.

As in the case of measurements of angular luminance and color variations, the most comprehensive and accurate measurements of the angular reflectance properties of a display are obtained using goniometric methods, yielding the bidirectional reflectance distribution function (BRDF) (Kelley et al. 1998). As for other angular measurements, simplified approaches are under development based on imaging technologies, but these have not yet gained international acceptance and are outside the scope of this chapter (see chapter "▶ Measurement Devices" for further information).

Temporal Performance (Motion Blur)

Measurements of the temporal performance of a display relate to the degree of image persistence for a dynamic image (see chapters "▶ Temporal Effects" and "▶ Standards and Test Patterns"). These measurements are particularly important for video images containing fast-moving, high-contrast targets, such as television coverage of football and tennis (where motion blur can cause the fast-moving ball to be hard to distinguish). The issue of motion blur has become more important with the advent of new displays, such as LCD screens. Unlike CRT displays, where the image is displayed only for a short time during each refresh cycle and is blank between each image, in an LCD display, the image is held on the screen during the entire refresh period. This means that for a fast-moving object in the image, the object

Table 2 Major potential sources of error with spectroradiometer (SR) and filtered broadband detector (BB) systems

Source of error	Type of instrument	Description	Evaluation/correction methods
Stray light	SR	Radiation scattered within the spectrometer is measured at a wavelength that does not correspond to its true wavelength, leading to errors in the measured spectral power distribution and in any calculated results, for example, tristimulus values	Evaluation: (a) measure the output as a function of wavelength for a large number of monochromatic inputs or (b) use cut-on or cut-off filters to investigate levels of stray light arising from particular spectral regions (e.g., no signal should be observed at wavelengths below the filter cut-on wavelength when the monochromator is set to wavelengths above the cut-on)
			Correction: this is possible using evaluation method (a) but is difficult and complex. A better approach is to select a spectrometer with low levels of stray light – typically this means using a scanning double monochromator
Spectral mismatch	BB	The match between the spectral response of a broadband meter and the target CIE standard observer function is never perfect, and residual mismatch errors lead to errors when comparing sources with different spectral characteristics. Errors of many tens of percent are common with colored sources such as displays	Evaluation: measure the spectral responsivity of the meter as a function of wavelength and compare with the desired function
			Correction: spectral mismatch errors can be minimized by calibrating the meter using a source with spectral characteristics close to those of the sources to be measured. A correction factor *F* can be applied if the target spectral function ($R(\lambda)$), the spectral responsivity of the meter ($s(\lambda)$), and the spectral power distributions of the reference and test sources ($S_{\mathrm{r}}(\lambda)$) and $S_{\mathrm{t}}(\lambda)$, respectively, are known: $F = \frac{\int S_{\mathrm{t}}(\lambda)R(\lambda)\mathrm{d}\lambda \times \int S_{\mathrm{r}}(\lambda)s(\lambda)\mathrm{d}\lambda}{\int S_{\mathrm{t}}(\lambda)s(\lambda)\mathrm{d}\lambda \times \int S_{\mathrm{r}}(\lambda)R(\lambda)\mathrm{d}\lambda}$
Wavelength scale	SR	Wavelength errors result in the measured irradiance or radiance values being assigned to an incorrect wavelength. This also impacts on quantities derived from spectral measurements, such as tristimulus values	Correction: calibrate the wavelength scale of the spectrometer at several wavelengths covering the wavelength range of interest, for example, by using monochromatic emission lines from a low-pressure discharge lamp or several laser lines
			Note that wavelength errors can vary significantly across the spectral region of interest, and even relatively small shifts (less than 1 nm) can result in a change of several ΔE^*_{ab} units for some display colors

Polarization	SR and BB	The optical radiation from some displays (e.g., LCDs) is highly polarized, and this can lead to significant errors if the responsivity of the detector system is polarization sensitive. Polarization effects can be wavelength dependent and can lead to errors in measured color or luminance values	Evaluation: make measurements of a uniform, nonpolarized light source (such as a luminance gauge) through a polarizer that is rotated to several different positions in turn. Any variation in the measurements is due to polarization sensitivity of the detector
			Correction: if the detector system does show polarization sensitivity, corrected results should be calculated from the mean of two measurements made at orthogonal polarizations
Linearity	SR and BB	The output signal does not vary in proportion with the input quantity	Evaluation can be assessed by measuring the output value for a number of known input values that span the range of inputs over which the instrument will be used. Often checked using calibrated neutral density filters, lamps of different intensities, or superposition techniques (Hopkinson et al. 2004)
			Correction: corrections can be applied, based on the evaluation measurements, but it is usually preferable to restrict the range of input values to those over which the instrument is linear
Dynamic range (saturation and noise)	SR and BB	The output of many displays (e.g., CRTs) can show large variations over the course of each refresh cycle. The dynamic range of the measurement instrument must be sufficiently large to avoid saturation at the peak of each pulse and to minimize the effect of noise on the signal at the low point of each cycle. This is important even for instruments in which the readings are averaged over several cycles, since saturation and noise effects can cause errors in the averaged signal	Evaluation: calibrate the system both with and without a neutral density filter in place and compare measurements of the display made under both conditions. Any difference in results indicates a probable problem due to saturation at the peak of each pulse
			Correction: calibrate and use the system with a neutral density filter that provides sufficient attenuation to ensure that no saturation occurs at the peak of the pulse, while also ensuring that signal levels are high enough to avoid problems due to noise

(continued)

Table 2 (continued)

Source of error	Type of instrument	Description	Evaluation/correction methods
Synchronization	SR and BB	The color of a display is rarely uniform over a refresh cycle, so correct results will only be obtained if the exposure time is an exact integer multiple of the display refresh period. Any partial cycles captured will distort the measurement result	Correction: if possible, the instrument should be synchronized with the refresh cycle of the display and set so that the measurement exposure time captures an integer number of cycles (here, “synchronization” means that the sampling time of the measuring instrument is directly related to the refresh rate of the display, not that the measurement is initiated at a particular time in the display cycle). If this is not possible, a long measurement time should be used, so that the number of whole refresh cycles is large compared to the number of part cycles captured
Bandwidth and step interval	SR	The choice of spectral bandwidth for a measurement is a compromise between signal level and spectral resolution. A wide bandwidth gives a high signal level and improved signal to noise ratio but at the cost of the resolution of narrow peaks, which may lead to errors, for example, in the calculation of tristimulus values. The step interval should be an integer multiple of the bandwidth, and to avoid significant errors in calculated tristimulus values, intervals of no greater than 5 nm should be used	Evaluation: bandwidth can be measured by scanning through a monochromatic line at very fine wavelength intervals and measuring the full width at half maximum. Note that the band-pass function may not remain the same size and shape over the entire wavelength range
			Correction: methods for correcting for bandwidth and step interval are available (Woolliams et al. 2011) but these require detailed knowledge of the band-pass function at all wavelengths and are generally not easy to apply. Instruments with poor slit profiles (e.g., highly nonsymmetrical) or where the step interval is not an integer multiple of the bandwidth are best avoided

position is correct for only a fraction of the time, and the eye interprets this as the object being blurred. In practice, there are two contributors to motion blur: the rise and decay time of the pixels and the hold time. The former can be measured using a fast photodiode and the latter is dictated by the display drive electronics.

Basic Measurement Instrumentation

As described in chapters "▶ Measurement Instrumentation and Calibration Standards" and "▶ Measurement Devices," most measurements of a display are made using either a spectroradiometer (Commission International de lÉclairage 1984), which provides measurement results as a function of wavelength, or a filtered broadband detector (Commission International de lÉclairage 1982), which is designed to give an approximation to one or more of the CIE standard observer functions. The different characteristics of these instruments can lead to different, but in each case significant, measurement errors, as summarized in Table 2.

Both types of instrument are typically calibrated using a stable and reproducible reference source, such as a luminance gauge. The reference source may be calibrated in terms of its luminance, its chromaticity, or its spectral output (usually absolute spectral radiance) as a function of wavelength by a laboratory that is traceable to national standards. The instrument is calibrated by comparing the measured values for the reference light source with the calibration data, yielding a correction factor or factors. All instruments will show some drift in calibration with time, so it is important to check the calibration at regular intervals. Furthermore, reference sources also drift, both with time and with usage, so it is important that these are recalibrated at regular intervals by a laboratory providing measurements that are traceable to national standards.

Summary

The key measurements required in order to characterize the performance of a display are luminance, color, spatial uniformity, angular distribution, reflectance, and temporal characteristics. These provide basic, underpinning information relating to the quality, usability, and legibility of the display under different conditions of use. This section has provided an overview of the methods, instrumentation, and major sources of potential error and uncertainty associated with these measurements; more details on all these aspects are provided in Sect. 11, "Display Metrology."

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Further Reading

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