

Colorimetry: Examining the Methods and Tools for Measuring and Analyzing Color

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Color is a psychophysical phenomenon, and perception of color is a subjective judgment. But color can be measured by several different methods. The four major colorimetric methods in use today are color matching, color temperature, tristimulus colorimetry and spectroradiometric measurement.

Let us begin by examining the four methods:

- **Color Matching** by comparison of physical samples, using a human observer to judge when a match is achieved. (An example of this is the Munsell system, which includes several hundred color chips.)

- **Color Temperature** measurement (for illuminants only).

- **Tristimulus Colorimetry**, using 3 or 4 color filters to match the CIE tristimulus spectral response functions.

- **Spectroradiometric Measurement** over the entire visual spectrum, in order to completely define the spectral distribution. (The spectral data may or may not be used in conjunction with the CIE system to compute chromaticity coordinates.)

Color matching is useful but difficult. It is time-consuming and is prone to subjective errors. Signifi-

cant errors can also be caused by viewing the samples under different types of light sources, called *metamerism*. It is also impractical for specifying illuminants, since it is difficult to prepare a *standard color light source*.

Color temperature

The concept of color temperature arises from the apparent color of an object as it is heated to various temperatures. All objects emit light when sufficiently hot. Changing the temperature of the object changes the intensity and color of the emitted light. A horseshoe, for example, glows dull red when first heated, then red-orange. In a steel mill, molten iron appears yellowish-white. The tungsten filament of a studio lamp is hotter yet and emits white light. An object which is hot enough to glow is said to be *incandescent* — hence the term for heated-filament bulbs.

A special class of incandescent objects emits radiation with 100 percent efficiency when heated (called emissivity); scientists call this group of ideal objects blackbody radiators. In particular, an ideal blackbody glows with a color which depends only on the object's temperature. This makes blackbody temperature an appealing basis for a color standard.

By adjusting the temperature of a blackbody, we produce a wide range of color sensations. We can now identify these color sensations by specifying the blackbody temperature in Kelvin degrees (equal to Celsius plus 273). Thus — remember that color we saw when the blackbody temperature was 3200 K? Well, use a light source just that color.

Looking at the spectral distribution curves for blackbody radiators at different temperatures gives us a better picture of why the color changes (Figure 1). The curve for a low-temperature blackbody source shows that most of the radiation is infrared and not visible at all. In the visible region, more red light is radiated than

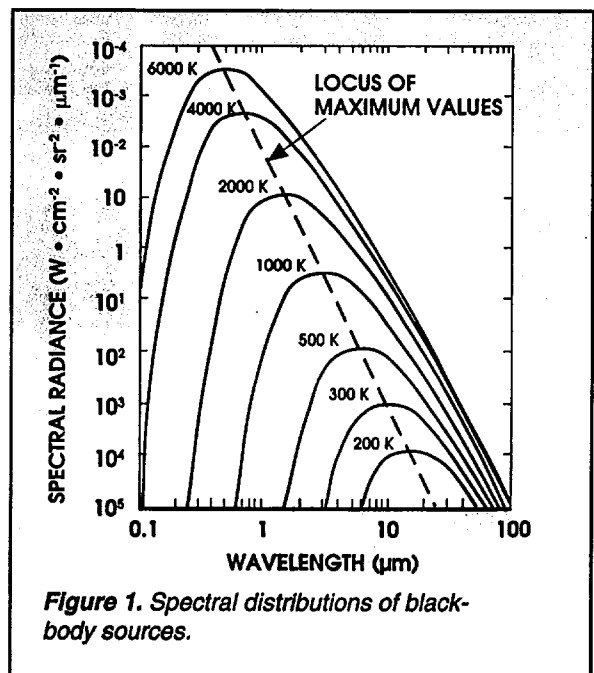


Figure 1. Spectral distributions of blackbody sources.

orange, and similarly down to violet. Sources of higher color temperature have maximum intensities at shorter wavelengths (bluer colors). A 3800 K source has its peak output at 750 nm in the deep-red, and has much higher output in the blue part of the spectrum than a low-temperature source, say, of 1500 K; similarly, a 5200 K source (similar to average daylight) peaks in the green region at about 550 nm, and has considerably higher output in the blue. At temperatures above 6000 K, the peak falls in the violet end of the visible spectrum and the source appears very bluish.

Although the concept of color temperature refers to sources that are, or are very close to, blackbody radiators, there are other sources that are near the locus that can be described as having a correlated color temperature whose color is nearly equal to a source that falls on the Planckian locus (Figure 2). A source with a correlated color temperature would appear to be the same color as a source on the locus although it has a slightly different set of color coordinates (defined in the next section). If we could graph a set of points above and below a point on the locus with the same correlated color temperature, we would have a graph of a constant correlated color temperature line (or an isotherm line).

By experimentation, it was found that the eye could detect small changes in color temperature, and this ability was closely approximated by the reciprocal of the color temperature times 10^6 . A term for this, the *mired* (microreciprocal degree), came to be used. Today, it is called the *mirek* or microreciprocal Kelvin, μK^{-1} . Color-temperature-raising filters are specified in mireds or in mireks.

An example might clarify matters. Assume we want to raise a 2000 K source to 3333 K. Using the mirek formula:

$$\begin{aligned} \frac{10^6}{\text{K}} &= \frac{1,000,000}{2000 \text{ K}} = 500 \text{ mirek} \\ &= \frac{1,000,000}{3333 \text{ K}} = 300 \text{ mirek} \end{aligned}$$

We have a minus 200 mirek shift (300 to 500). We would then select a minus 200 mirek filter to shift a

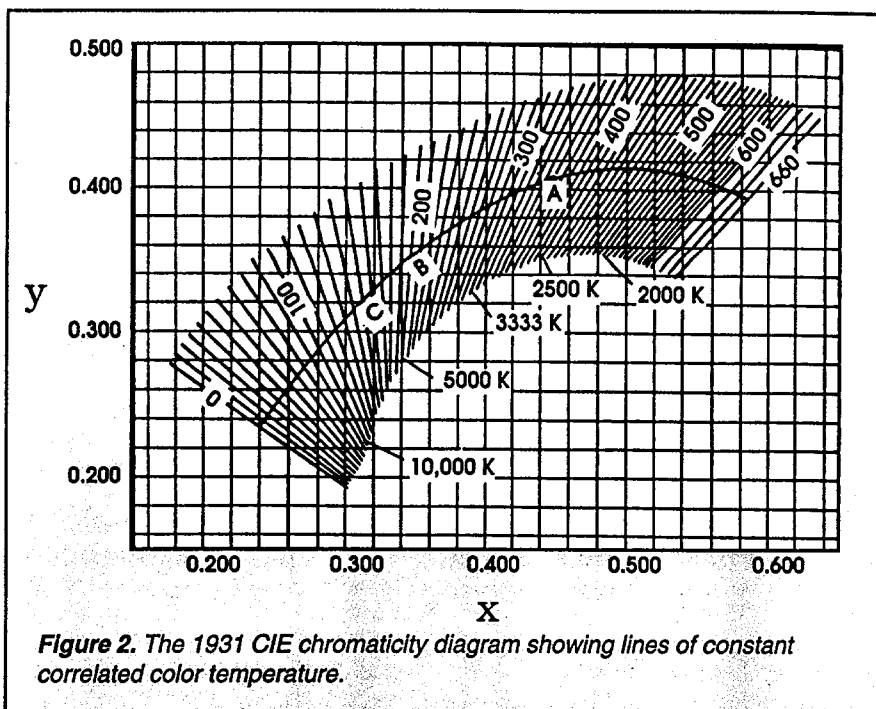


Figure 2. The 1931 CIE chromaticity diagram showing lines of constant correlated color temperature.

2000 K blackbody source to 3333 K.

How do we measure color temperature? The specification of color temperature completely defines the spectral distribution characteristics of a blackbody source. Since the spectral distribution is defined, a color temperature measurement may be made by simply measuring the ratio of energies in two known spectral bands within this distribution. Although the choice of wavelength bands is not critical, historically these measurements are made through a blue filter and a red filter.

The ratio of the readings may be converted to color temperature either by use of a calibration curve, or by calibrating a special meter scale, using known color temperature standards.

This technique is often used for color temperature calibration of photometers, which are generally used for measurement of near-blackbody sources, such as tungsten lamps. Color temperature curves from 1500

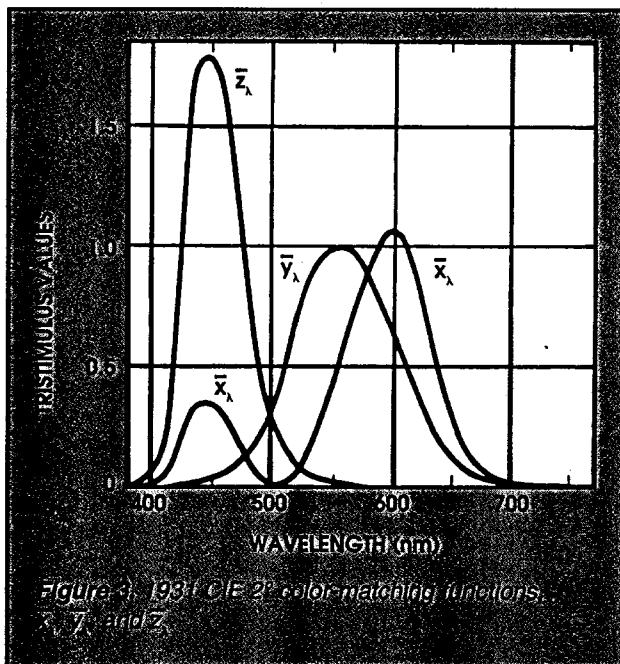


Figure 3. 1931 CIE 2° color-matching functions.

to 10,000 K can be supplied. As long as the light being measured closely approximates a blackbody source, the results are quite accurate. However, many important light sources — such as CRTs, fluorescent lamps, arc lamps and even daylight — are not ideal blackbody sources. A single blue-to-red ratio color temperature reading of these light sources can be completely erroneous due to lack of information about the green portion of the spectrum.

This problem can be somewhat overcome by the use of a three-color meter. This instrument is similar to a conventional color temperature meter, but uses a second ratio measurement to improve the accuracy of the reading; this second ratio is the green-to-red ratio. The green-to-red ratio reading may be called the green/red color temperature, and provides additional information about the source. First and foremost, if the green/red color temperature is different from the blue/red, this is an immediate indication that the source is not a blackbody. In this case, reporting both blue/red and green/red values gives a rough indication of the spectral distribution of the source — which is much more meaningful than the blue/red alone.

Color temperature, especially of sources far from the Planckian locus, can also be determined by tristimulus colorimetric and spectroradiometric methods with the aid of a look-up table.

Tristimulus colorimetry

Tristimulus colorimetry is based on the assumption that any color can be matched by a suitable combination of three primary colors (stimuli) — generally red, green and blue.

The most important system of tristimulus colorimetry is the CIE system. The CIE (Commission Internationale de l'Eclairage) system is based on international agreement on a particular set of primary stimuli and corresponding spectral sensitivity functions. (The R,G,B tristimulus system is another such system, and is in wide use in the television broadcast industry.)

Although the CIE system was based on actual measurements of the color sensitivity of typical human observers, the CIE 2° primaries (X,Y and Z) are unreal mathematical entities. They were chosen to transform the real data in order to improve the system's utility by eliminating negative coefficients of the primaries, by having the coefficients of one of the

three primaries equal to the luminosity function, and by making the other two primaries have zero luminosity.

The coefficients of these imaginary primaries that are required for a human observer to match a unit amount of monochromatic energy at any wavelength from 380 to 760 nm (or from 360 to 830 nm) are the all-important CIE 2° color-matching functions — x_λ , y_λ and z_λ . These functions are shown in Figure 3. It is important to note that the y_λ function is (by definition) identical to the photopic luminous efficiency function, $V(\lambda)$.

Although the spectral tristimulus values do not represent the actual spectral sensitivity of the human eye, it is conceptually easier to think of them as if they did. This is because they are used to weigh the spectral power distribution of a light source (P_λ) to produce an integrated response value. These values, (capital) X, Y and Z, are called the tristimulus values for a particular color source. These values can be thought of as coefficients of a vector in three-dimensional color space, such that the color, C, is defined as follows:

$$C = X\vec{X} + Y\vec{Y} + Z\vec{Z}$$

Now, it is difficult to visualize colors in terms of three-dimensional vectors, so the CIE system provides another transformation to enable the color to be visualized as it would be projected on a flat (two-dimensional) surface. This is the CIE chromaticity diagram with its familiar horseshoe shape (Figure 4). The axes of this graph are the CIE chromaticity coordinates, (small) x and y, which are derived from the X, Y and Z tristimulus values by using the following equations:

$$x = \frac{X}{X + Y + Z} = \frac{\text{Red}}{\text{Red} + \text{Green} + \text{Blue}}$$

$$y = \frac{Y}{X + Y + Z} = \frac{\text{Green}}{\text{Red} + \text{Green} + \text{Blue}}$$

(In the CIE system, it is adequate to use only x and y to specify chromaticity; z, of course, is always equal to 1-(x+y).)

The center of the diagram is white (neutral or achromatic) and occurs at 0.333 x and y. The hues

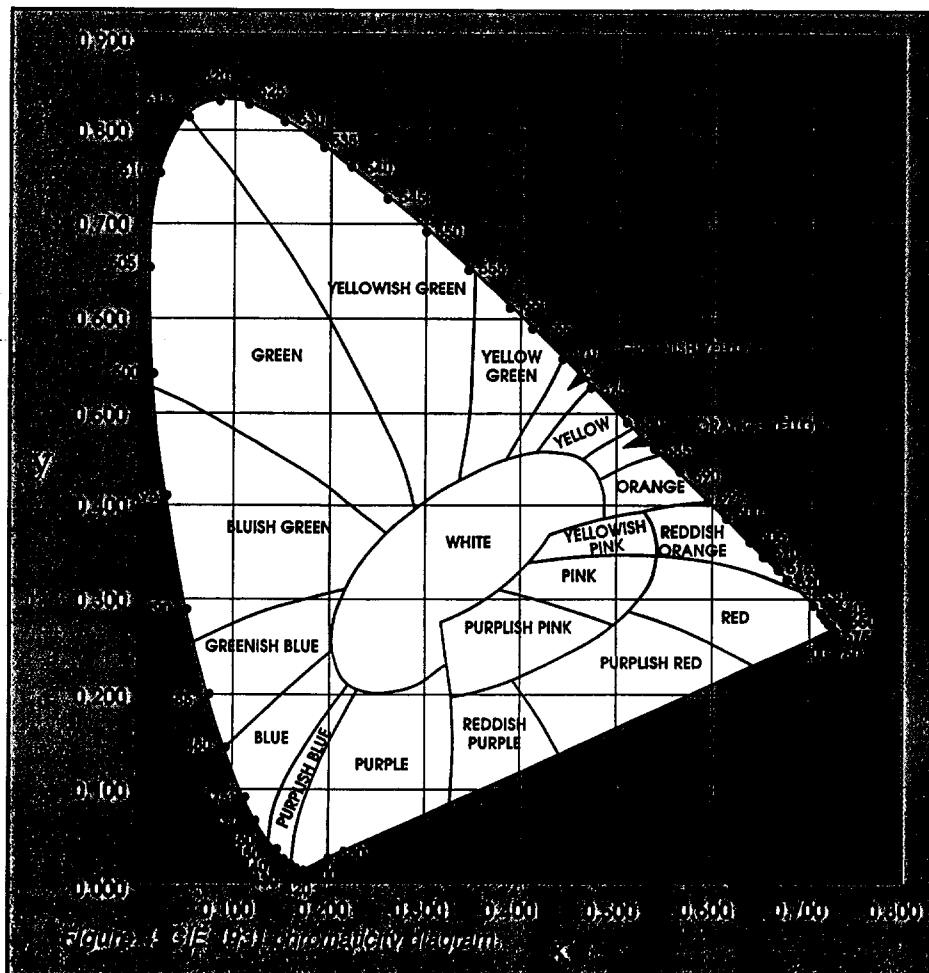


Figure 4: CIE 1931 Chromaticity Diagram

(colors) become more saturated (pure) as we move from the center to the perimeter of the horseshoe, which is called the spectrum locus.

Specification of the two CIE chromaticity coordinates x and y completely specify the color or chroma of a source or object; that is, its hue and saturation. The capital Y value — which derives from the y_λ function — completely specifies the brightness or luminosity. Together, these three numbers completely specify a color in the CIE system — values for hue, saturation and lightness vectors.

If a photometer can be equipped with filters such that its spectral response matches that of the three CIE spectral tristimulus matching functions (x_λ , y_λ and z_λ), the output of the instrument will be a direct measurement of the tristimulus values of the source being measured (X , Y , and Z). To a reasonable approximation this can be commercially achieved.

Generally, three filters are used. The photopic filter is identical to the y_λ function, and is used unmodified. The blue filter is trimmed to closely match the z_λ function. The red filter is then trimmed to match the red portion of the x_λ function from approximately 500 to 760 nm.

It is not practical to build a single filter which can match the entire x_λ function from 380 to 760 nm, so the 380- to 500-nm portion is disregarded and compensated in the calibration. On some high-performance photometer/colorimeters, a fourth filter is added which matches the 380 to 500 nm portion of the x_λ function. This fourth filter, which is designated the X_b or X' filter, is added because it results in a slight improvement in measuring accuracy, especially when measuring sources with much blue content.

To use the system, the operator makes sequential measurements through each colorimetric filter, records them, then calculates the tristimulus values and x, y chromaticity coordinates using the equations above.

If the unknown source is not a near-blackbody, first the operator must calibrate the colorimeter. This is done using a colored light source (or light source and colored filter

TABLE 1.
SPECTRORADIOMETRIC AND
COLORIMETRIC CALCULATIONS

Chromaticity coordinates are computed, from tristimulus values (X, Y, Z) as follows:

$$\begin{aligned} \text{1931 CIE:} \quad & x = X/(X+Y+Z) \\ & y = Y/(X+Y+Z) \\ & z = 1-(x+y) \\ \\ \text{1960 CIE:} \quad & u = \frac{4X}{X+15Y+3Z} = 4x/(-2x+12y+3) \\ & v = \frac{6Y}{X+15Y+3Z} = 6y/(-2x+12y+3) \\ \\ \text{1976 CIE:} \quad & u' = \frac{4X}{X+15Y+3Z} = 4x/(-2x+12y+3) \\ & v' = \frac{9Y}{X+15Y+3Z} = 9y/(-2x+12y+3) \end{aligned}$$

Color difference equations, where ΔE^* is the color difference, are computed as follows:

$$\begin{aligned} \Delta E^*(L^* u^* v^*) &= ((\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2)^{1/2} \\ L^* &= 116(Y/Y_0)^{1/3} - 16 \\ u^* &= 13L^*(u' - u'_0) \\ v^* &= 13L^*(v' - v'_0) \\ \\ \Delta E^*(L^* a^* b^*) &= ((\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2)^{1/2} \\ L^* &= 116Y(Y/Y_0)^{1/3} - 16 \\ a^* &= 500((X/X_0)^{1/3} - (Y/Y_0)^{1/3}) \\ b^* &= 200((Y/Y_0)^{1/3} - (Z/Z_0)^{1/3}) \end{aligned}$$

Where X_0, Y_0, Z_0, u'_0 and v'_0 are the coordinates of a CIE standard Illuminant (such as D_{65}), $Y/Y_0 > 0.008856$.

The CIE — a nongovernmental international standards organization — has changed its calculations for color measurements over the years. All of the equations, however, use tristimulus values to compute chromaticity coordinates. These coordinates are then used to develop color difference equations.

Photometric quantities (such as luminance, L_v) can be accurately computed from spectroradiometric data by the following formula:

$$L_v = 683 \int P(\lambda) \cdot V(\lambda) \cdot d\lambda$$

where $P(\lambda)$ is the measured spectral radiance at wavelength λ , and $V(\lambda)$ is the CIE 1931 "Photopic luminous efficiency" function.

Colorimetric quantities ("tristimulus values") are computed for three similar integrations of the measured spectral distribution data:

$$X = \int P(\lambda) \cdot \bar{x}(\lambda) \cdot d\lambda$$

$$Y = \int P(\lambda) \cdot \bar{y}(\lambda) \cdot d\lambda$$

$$Z = \int P(\lambda) \cdot \bar{z}(\lambda) \cdot d\lambda$$

where $P(\lambda)$ is the measured spectral power distribution, and $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ are the CIE 1931 color-matching functions.

Radiometric power in a given spectral band can be computed by simply integrating the spectroradiometric power between the desired wavelength limits, λ_1 and λ_2 .

$$P = \int_{\lambda_1}^{\lambda_2} p(\lambda) \cdot d\lambda$$

Automatic, computer-controlled spectroradiometers can calculate photometric quantities, colorimetric quantities and radiometric power from spectroradiometric data.

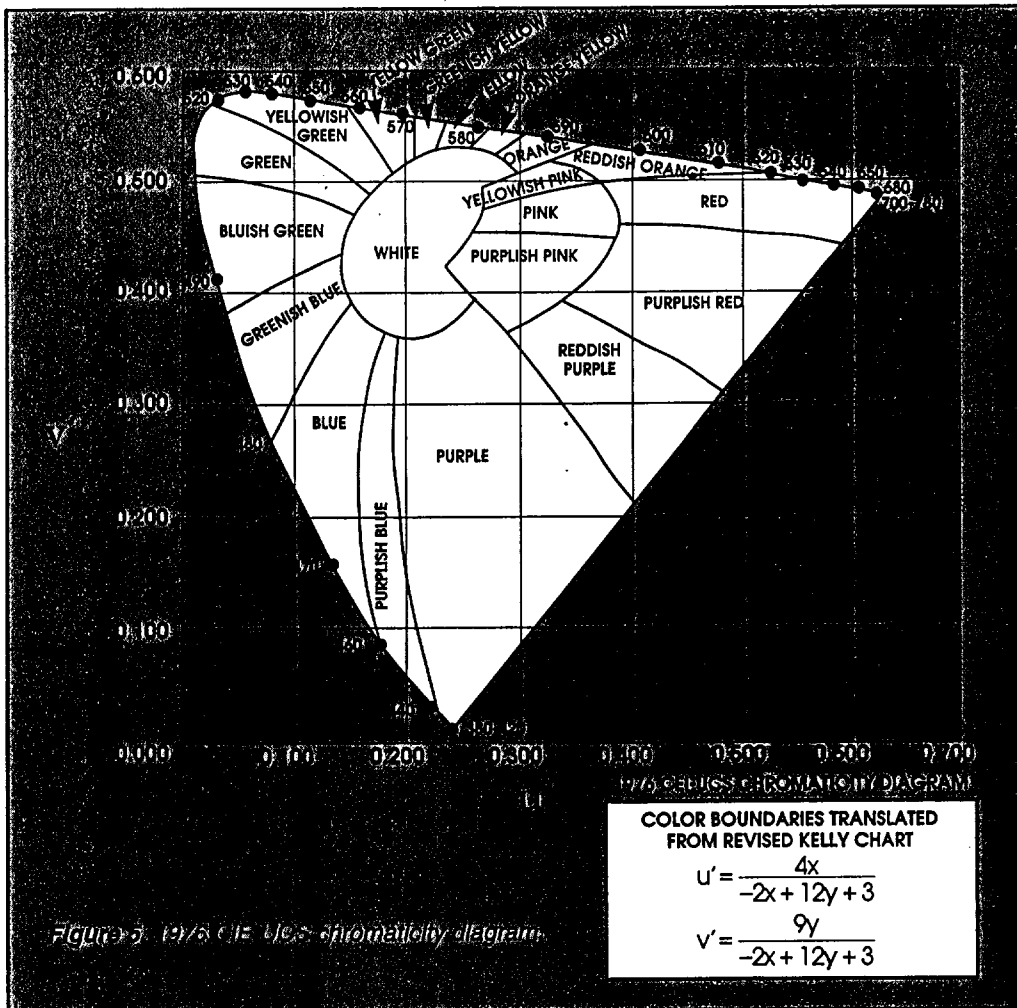


Figure 5 1976 CIE UCS chromaticity diagram

combination) whose tristimulus values or chromaticity coordinates are precisely known. Furthermore, since the spectral sensitivity functions of the colorimeter do not exactly match the CIE spectral tristimulus functions, best results will be achieved if the calibrating source is very similar in color and spectral distribution to the source being measured.

Obviously, the more closely the colorimeter spectral trim matches the CIE color-matching function, the better the colorimeter's accuracy when measuring sources with different spectral energy distributions. When proper calibrating sources are available, photometers with all four tristimulus filters have proven to be accurate to within ±0.003 to ±0.005 chromaticity units.

In 1964, the CIE recommended a second set of tristimulus color-matching functions, called the CIE 10° Supplementary Observer, for wider fields of view. These functions

are somewhat broader than 2°, and are designated with a subscript 10, for example x_{10} and y_{10} . The 10° functions are sometimes specified for television.

Spectroradiometric methods

If one has the time and the complex measuring equipment, the spectroradiometric method is the most accurate and complete method of specifying color. In this method, a calibrated spectroradiometer is used to measure the complete spectral power distribution of a source.

Spectroradiometers utilize a dispersive element (prism, wedge or grating) that splits up the input light into its spectral energy components. The spectroradiometer measures the energy in each of those spectral boxes individually, resulting in an output of energy vs. wavelength of the input light.

The spectral data can be analyzed visually and/or compared to data from

other sources. However, the best use of spectral data is to calculate the CIE tristimulus values by mathematically integrating the data with the CIE x_λ , y_λ and z_λ functions. The tristimulus values are then used to compute CIE chromaticity coordinates and luminosity, which provide a complete description of the color.

Later experimentation has shown that the 1931 CIE data was severely lacking in specifying color differences. One minimum perceptible (or just noticeable) color difference (mpcd or jnd) varied throughout the horseshoe diagram. The 1960 UCS (Uniform Color Space) diagram (a linear transformation of the 1931 curve) establishes $u-v$ coordinates. The 1960 UCS diagram is particularly useful for computing color temperature since the diagram was constructed so that the isothermperature lines are perpendicular to the Planckian locus, thereby making interpolation easy.

Both the 1931 and 1960 systems assumed luminosity (brightness) to be held constant. Since luminosity was not allowed to vary, colors such as brown do not fall anywhere on the two-dimensional diagrams. The 1976 CIE-LUV/LAB three-dimensional color difference formulas remedy the problem. The 1976 CIE-UCS color space (Figure 5 — another linear transformation of the 1931 diagram) is used in specifying colors for avionics displays, since a three-dimensional color tolerance radius can be specified under broad ambient conditions. Table 1 summarizes spectroradiometric and CIE colorimetric measurement equations.

About spectroradiometers

All visible-range spectroradiometers have several things in common: radiant power or flux is collected; it is dispersed into spectral components; the spectral components are detected, converted to electronic

signals and processed mathematically; then the results are output. In the processing phase, the unknown spectral energy distribution (SED) is compared to a standard (known) SED that had been previously measured with the same spectroradiometer (for example, vs. a spectrally calibrated tungsten-halogen lamp).

Energy collection can be accomplished by using an integrating sphere, a high-reflectance plate, remote-sensing optics (such as objective lenses), cosine receptors or fiber optic probes. Because these collectors usually are not perfectly spectrally nonselective, spectroradiometric correction factors usually must be determined for each collection geometry used.

Dispersion is usually accomplished in a spectrometer by prisms or diffraction gratings. Bandwidth is the spectral width of the data that is analyzed at each spectral increment. Bandwidths are usually specified from the half-maximum amplitude widths (full width half maximum, or FWHM). The wider the bandwidth is, the greater the throughput and the lower the resolution.

Increment or jog interval is how often data is taken. The CIE recommends that the bandwidth and interval be the same (or the bandwidth be evenly divisible by the interval). For accurate colorimetry of spiky sources such as a CRT red phosphor, bandwidths and intervals of 5 nm or smaller should be used. For highest colorimetric accuracy the CIE now recommends 1 or 2 nm bandwidths and intervals, and extended tristimulus functions (from 360 to 830 nm).

For ultraviolet, visible and near-infrared spectroradiometers, usually only two types of detectors are used. Either high-gain vacuum phototubes (PMTs) or silicon photodiodes are the usual choices. For the infrared there are many choices depending on sensitivity and spectral range. Pyroelectrics, PbSe, HgCdTe and PbS are examples.

Common sources of error for spectroradiometers are: calibration errors; stray light; signal-to-noise; wavelength scale; slit-function (bandwidth); polarization; detector instability; detector time constant; and collection geometry. With proper

instrument design and measurement techniques, most of these errors can be minimized.

A *slow-scan* spectroradiometric system is called slow-scan or serial acquisition method because the dispersive grating in the monochromator (single color) is physically rotated by a stepping motor. After each increment, the photodetector (photomultiplier or silicon diode) detects the amount of spectral energy at that wavelength and transfers it to the amplifier. From there it goes to the computer for calculation using supplied software. After all data points have been taken, radiance, photon radiance, photopic and scotopic luminance, color coordinates, correlated color temperature, etc., can be readily computed. A spectral plot is often made, as well

as a point-by-point printout of spectral values.

One particular advantage of a high-resolution 1-nm slit is its ability to resolve minute color shifts. For example, a red LED will shift its color (and thereby its luminous intensity) to longer wavelengths as increased current raises the diode junction temperature.

Another type of spectroradiometer, the *fast-scan* variety, uses a self-scan diode array as a detector. The dispersive element of the polychromator (multicolor) does not actually move. The entire dispersed spectrum is *mapped* simultaneously onto the detector segments, so this is called a parallel acquisition or optical multi-channel spectrometer system. Each segment of the array measures a slightly different color. The array is

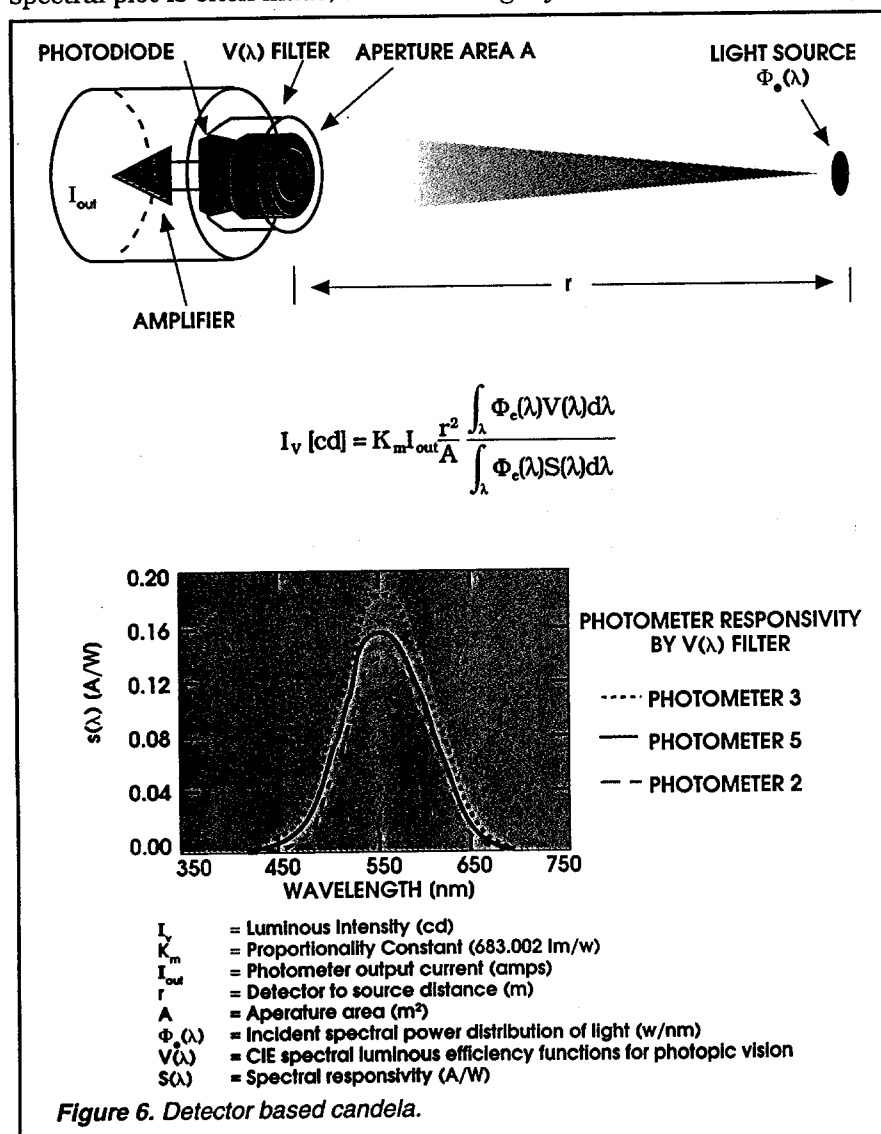


TABLE 2.
1986 SPECTRAL IRRADIANCE SCALE UNCERTAINTY (3 σ)
IN PERCENT

	250 nm	500 nm	525 nm	700 nm	1000 nm	1500 nm	2000 nm	2400 nm
I. NIST SPECTRAL RADIANCE SCALE								
a. Absolute error (with respect to SI units)	1.41	1.01	0.55	0.49	0.41	0.44	0.70	1.16
b. NIST long term reproducibility (without T_{Au} , see Table 1)	0.58	0.42	0.25	0.34	0.33	0.39	0.69	1.15
II. RADIANCE TO IRRADIANCE TRANSFER								
a. Systematic errors	0.36	0.31	0.27	0.26	0.26	0.25	0.25	0.25
b. Random errors (3 σ precision)	0.43	0.11	0.08	0.84	0.86	1.46	2.60	5.73
III. SPECTRAL IRRADIANCE SCALE UNCERTAINTY (QUADRATURE SUM)								
a. With respect to SI units	1.52	1.06	0.62	1.01	0.99	1.55	2.71	5.85
b. NIST long term reproducibility	0.81	0.53	0.38	0.94	0.96	1.53	2.70	5.85

electronically scanned (instead of mechanical scanning) so an entire spectral scan cycle can occur in thousandths of a second rather than taking up to several minutes as it often does with slow-scan systems.

By cooling and adding (digitally integrating) many successive scans, or by integrating on chip, sensitivity can be enhanced. With the further improvement of image intensification, the self-scan diode array spectroradiometer's sensitivity approaches that of a photomultiplier-type. The fast-scan optical head can be mated with a microprocessor, resulting in a near-real-time spectral analysis system that can be used for temporal analysis of spectra (spectral change as a function of time). An application would be flashlamp or muzzleflash evaluation.

Optical spatial scanning

Optical scanners use imaging optics to remotely sense light. As with spectral scanners, spatial scanning can be performed either mechanically or electronically. Mechanical scanners move a lens or an aperture. The optical signal is detected by a photosensor. (If the spatial scanner is a scanning microphotometer, the sensor is photopically corrected.) The electrical signal is amplified and output to an x - y recorder or computer/plotter. The recorder/plotter

also receives positional information from the scanner. The y axis is light-level and the x axis is displacement.

Electronic spatial scanners use a focal plane array, linear or area (matrix). The incoming light is mapped onto the array where it is detected by the individual pixels (picture elements). Since the geometry of the detector array is well defined, positional information is accurately determined by polling the detectors sequentially. The signals are then amplified and output as above.

Newer systems use a CCD or vidicon tube camera, and an image capture board (in a host PC computer). These video-based photometer/radiometer/colorimeter systems are often interfaced with positioners and used in automatic test and evaluation (ATE) applications.

Recent use of color cathode-ray tubes (CRTs) in military and commercial aircraft has created a requirement for critical measurement of such CRT parameters as color, line-width, symbol location, peak brightness, distortion, contrast ratio (MTF/CRF), gray scale, displacement, position sensing, spot/line contour and brightness uniformity.

In the past, several different instruments were required to perform all these functions, not the least of which was a large computer. Today's use of microprocessors or desktop

PC computers combined with spatial/spectral scanning (microphotometry/microspectroradiometry) makes it possible to automatically perform all these measurements with one test-set.

Spatial scanning techniques can also be used to create ultraprecise angular scanners. Recent military and commercial airplanes come equipped with head-up-displays (HUDs). CRT images are projected up onto a combiner-glass in front of the pilot. Displaying critical dynamic aircraft parameters in this way eliminates the necessity of the pilot having to look down at the instruments while flying the plane. These projected images are collimated (projected at infinity). An angle-scanning measuring instrument thereby mimics the rotation of the pilot's head. Video-based photometers have the high geometric accuracy required of this demanding application.

Integrated energy exposure

All of the previous discussion related to the measurements of the average value of steady-state light sources (i.e., light sources that are continuously on, or relatively constant with respect to time). This type of measurement is called average power measurement.

Another important class of light measurements is called integrated

energy or integrated exposure; these measurements are usually (but not always) related to light sources that vary rapidly with time — such as flashlamps or pulsed LEDs. Integrated exposure measurements are also useful for measuring the effect of constant light sources that are used to expose photosensitive materials, such as photographic films and photoresists, for time periods ranging from a fraction of a second up to 20 or 30 s.

Integrated energy (or exposure) is defined as the integral of instantaneous power and time:

$$\text{Energy} = \int_0^T \text{Power} dt.$$

In the special case of a constant power light source being used to expose a photosensitive material for a known time, integrated energy or exposure simplifies to:

$$\text{Exposure} = \text{Power} \times \text{Time}$$

Each of the average power parameters discussed in earlier sections has a corresponding integrated energy homolog. The units of the integrated energy parameters are the same as the average power parameters but with the addition of the suffix -seconds; for example, illuminance expressed in footcandles becomes footcandle-seconds when integrated. The average power radiometric units based on the watt become energy units based on the joule when integrated, since 1 joule equals 1 watt-second; for example, microwatts per square centimeter becomes microjoules per square centimeter when integrated.

There are many applications for the measurement of pulsed-light sources. These include flashlamps, strobe lights, pulsed LEDs and pulsed lasers.

Another group of pulsed light measurements require an instrument with a very fast response time. Typical applications include the measurement of high-speed scanners, CRT phosphor persistence, turn-on and turn-off times of liquid crystal displays, and analysis of the ripple of light sources. These instruments have a video bandpass and are used in conjunction with an oscilloscope to measure peak luminance/

radiance, and the temporal light intensity profile of a source.

Photometric standards

Originally, the photometric scale in the USA was based on standard candles. This was followed by: wick lamps with hydrocarbon liquids; a blackbody radiator operating at the freezing point of platinum; monochromatic radiation having a specified frequency and radiant intensity; and, in 1986, by a blackbody radiator operating at the freezing point of gold. The primary standard for all photometric calibrations is now based on absolute detectors.

The new detector-based method for realizing the photometric scale, the candela, employs a group of eight reference photometers constructed using silicon photodiodes matched with filters to mimic the CIE spectral luminous efficiency function for photopic vision (Figure 6).

Since it is generally not practical to use these detector-based standards on a routine basis, most calibration laboratories use the primary detector-based photometric standards to calibrate specially selected tungsten or tungsten-halogen incandescent lamps as secondary standards. These secondary standards are then used in a precise, specified way to calibrate photometers/radiometers. The lamps are properly positioned, baffled, ventilated and operated from a precisely current-regulated power supply.

The lamp itself is calibrated in terms of luminous intensity in a specified direction (horizontal candlepower). Thus, it can be used directly for candlepower calibration.

To use the standard lamp for illuminance calibrations, the distance between the lamp and the photometer

is varied to produce the desired illuminance level. The following equation is used:

$$E = \frac{C.P.}{D^2}$$

where E is illuminance, C.P. is candlepower, and D is distance.

Luminance is defined as the luminous intensity per unit area of the source. Thus, a luminance measurement requires a uniform light source of significant size. A simple light bulb with a coil-type filament is inadequate for use as a luminance standard. In recent years, calibrated integrating sphere sources have been used as luminance standards. The integrating sphere source can be obtained with various sized spheres having different radiating areas. The luminance of an integrating sphere source is determined by measuring the illuminance and then computing the luminance from a knowledge of the area of the radiating sphere port and the distance that the illuminance measurement was made.

Radiometric standards

The NIST Spectroradiometric Scale is based on the radiance of a blackbody radiator operating at the freezing point of gold as defined by the Planck Radiation Equation. Figure 6 shows the derivation of the NIST Spectroradiometric Scales from the gold point blackbody. Traditionally, working primary standards that have been used in radiometry and spectroradiometry are a group of specially selected tungsten-halogen and tungsten ribbon filament lamps calibrated for spectral irradiance or radiance. These lamps are used to calibrate working secondary standards, which are sold to calibrating labs.

The tungsten-halogen lamps are

TABLE 3.
COLOR TEMPERATURE UNCERTAINTIES (3 σ)

COLOR TEMP	SYSTEMATIC UNCERTAINTY	TRANSFER PRECISION	TOTAL UNCERTAINTY QUADRATURE
2000	7.0	8.0	10.5
2400	9.0	8.0	12.0
2600	10.0	4.5	11.0
2856	12.5	3.5	13.0
3000	14.0	3.5	14.5

used directly to calibrate spectroradiometers for spectral irradiance response. They can also be used in conjunction with spectrophotometrically calibrated narrowband filters to calibrate irradiance meters over a given spectral range. Spectral radiance standards consist of tungsten ribbon filament lamps. When used to calibrate a spectroradiometer for spectral radiance response, the filament of the lamp is imaged onto the entrance slit of the monochromator. If the small size (about 3 x 10 mm) of the filament is not suitable for the calibration, an integrating sphere source can be used. The integrating sphere source is similar to that used as a large area luminance standard. However, calibration of the sphere source for spectral radiance is accomplished by measuring the spectral irradiance at a known distance and computing the radiance.

The use and operation of these lamps is similar to the use of photometric standard lamps — requiring extremely careful regulation of lamp current, position, orientation, etc.

Colorimetric calibration

The working primary standard for color temperature in the 1800 K-to-3000 K range is a group of tungsten lamps. Secondary standards made from these primary standards are supplied calibrated at various color temperatures. The most common standard value is that of CIE Illuminant A, which is 2856 K. (The CIE also specifies several other standard illuminants, but Illuminant A is the easiest to obtain.)

The most common method of standardizing CIE chromaticity is by supplying calibrated filters that are used in conjunction with specified black-body light sources, such as CIE Illuminant A mentioned above. These filters are measured spectrophotometrically for spectral transmission, and the data is used (in conjunction with the light source data) to compute the CIE chromaticity coordinates.

The accuracy of any photometric or radiometric measurement is limited by errors and uncertainties. Excluding obvious operator error, the major sources of error are:

1. Uncertainty of the basic calibration standard.

2. Errors and uncertainties in transferring the calibration from the standard to the measuring instrument.

3. Instrument errors, such as non-linearity, poor photopic match, cosine error, noise, range errors, polarization, temperature drift, internal stray light, etc.

4. Set-up errors, when measuring actual light sources in real-world environments, such as inclusion of stray light, nonuniformity of luminance within the measuring field, misalignment between source and photometer, etc.

The last item, set-up error, can be eliminated by careful operator techniques. However, the first three items will still limit the accuracy of the measurement.

If only relative measurements are required, the uncertainty due to the basic calibration standard can be eliminated. This leaves only items number 2 and 3 as limitations. Measurements made with most quality instruments have a relative accuracy on the order of 1 to 2 percent. Absolute accuracy (for a 1 σ uncertainty), on the other hand, is the root-mean-square sum of the relative accuracy and the absolute uncertainty of the basic calibration standard.

The absolute accuracy of any measurement is limited by the uncertainty of the calibrating standard. All photometer manufacturers are limited by the uncertainty of the calibrating standards maintained at the NIST. Absolute uncertainty in the 2- to 3-percent range is typical for most photometric measurements, yielding an overall uncertainty in the 3- to 5-percent range.

Radiometric standards tend to be more accurate, since they are absolute measurements. See Table 2 for the estimated uncertainty of the NIST standards of spectral irradiance. The absolute accuracy of color temperature standards provided by NIST is estimated to be within 5 to 20 K at 2856 K, and correspondingly higher at higher color temperatures (Table 3).

New standards

Traditionally, tungsten (or tungsten-halogen) lamps have been used for photometric/radiometric standards of light measurement. Today,

other standards are available. The standard LED is one example. LED measurements have long suffered from inaccurate measurement. Color response of instruments and geometric considerations of LED measurement are vastly different from those represented by tungsten standards. Standard LEDs solve this problem and international inter-comparisons assure consistent results.

Due to inherent stability, freedom from light memory, and consistency of response, state-of-the-art silicon detectors have recently been employed as transfer standards and as absolute standards. For example, from time to time a temperature-stabilized transfer package is made available from NIST to verify both absolute and relative accuracy of light measurement. By comparison with this detector transfer responsibility package, local standards can be created and accuracy verified. □

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