Color Temperature

Douglas A. Kerr, P.E.

Issue 4
November 8, 2005

ABSTRACT

Color temperature refers to a way of describing the chromaticity of a particular category of "white" light in terms of the chromaticity of the light emitted by a theoretical "black body radiator" at a certain temperature. An extension of the concept is used to characterize the chromaticity or a wider class of light. The concept is often used in describing light used to illuminate objects for viewing or for photography when accurate color rendition is critical.

BACKGROUND

White light

It may seem strange to talk about describing the chromaticity[1] of particular kinds of "white" light. Doesn't white light have a fixed, known chromaticity?

In fact, there is no single chromaticity which inherently qualifies as "white". To the human observer, there is quite a range of chromaticities which, in the appropriate context, will be perceived as "white".

Accordingly, in technical work involving the properties of white light, it is usually necessary to stipulate a particular chromaticity which will be considered "white". There are several such chromaticities that have been standardized for this purpose, including "illuminant C" and "Illuminant D_{65}". We will hear a little more about these later.

The black body

A *black body* is an object that absorbs all the electromagnetic radiation falling on it regardless of wavelength. When the concept is used in the context of visible light, we consider as a black body an object that exhibits that property over at least the range of visible wavelengths.

---

[1] *Chromaticity* is that aspect of light which most lay people think of as "color". Formally, *color* comprises both *chromaticity* and *luminance* (brightness).

Since the black body absorbs all the radiation falling on it, it reflects none. Thus a black body, not matter how illuminated, appears to the viewer to be **black**, hence the name.

Any object that absorbs radiation will also emit radiation unless it is at a temperature of absolute zero. The amount of radiation emitted, and its spectral distribution, depends on the temperature of the object and the nature of the object's surface. A black body is a specific type of surface in that regard. The spectral distribution of the light emitted by a black body at any given temperature may be calculated on theoretical grounds. That spectral distribution will be perceived by a human viewer as having a certain chromaticity (different for each temperature). Over quite a range of temperatures of the body, the resulting chromaticities are those that can reasonably be called "white".

THE CONCEPT OF COLOR TEMPERATURE

The Planckian (blackbody) locus

If we plot the chromaticity of blackbody[2] emission on the CIE chromaticity diagram[3] for a range of temperatures, we get a curve known as the *blackbody locus*, or *Planckian locus*.[4] The temperatures are usually expressed in the Kelvin scale—an "absolute temperature" scale—as for example, 6200 kelvin[5] or 6200 K [6]. The blackbody locus is illustrated on Figure 1.

The spectral distribution of blackbody radiation is continuous, with some energy at every wavelength (at least over the range of interest). As the temperature of the black body increases, the distribution shifts toward the shorter wavelengths. Accordingly, for higher temperatures, the chromaticity shifts toward blue hues; for lower temperatures, toward red hues.

---

[2] It is customary to present the phrase "black body" as one word when used as an adjective.

[3] A complete explanation of the CIE chromaticity diagram will be found in the companion article, "Color and Color Spaces", by this author.

[4] Named in honor of Max Planck, the German physicist responsible for the theoretical understanding of blackbody radiation. Planck said of this work, "... the whole procedure was an act of despair because a theoretical interpretation had to be found at any price, no matter how high that might be."

[5] Note that units whose names are based on the names of people nevertheless are not capitalized ("kelvin"), but their symbols are ("K").

[6] Not "degrees Kelvin" (or °K), as had been the convention at an earlier time.

Color temperature

If we are interested in light of some arbitrary "white" chromaticity which happens to lie on the blackbody locus, we can precisely describe its chromaticity merely by stating the temperature at which a black body would emit light of that same chromaticity. That temperature is said to be the *color temperature* of the light of interest.

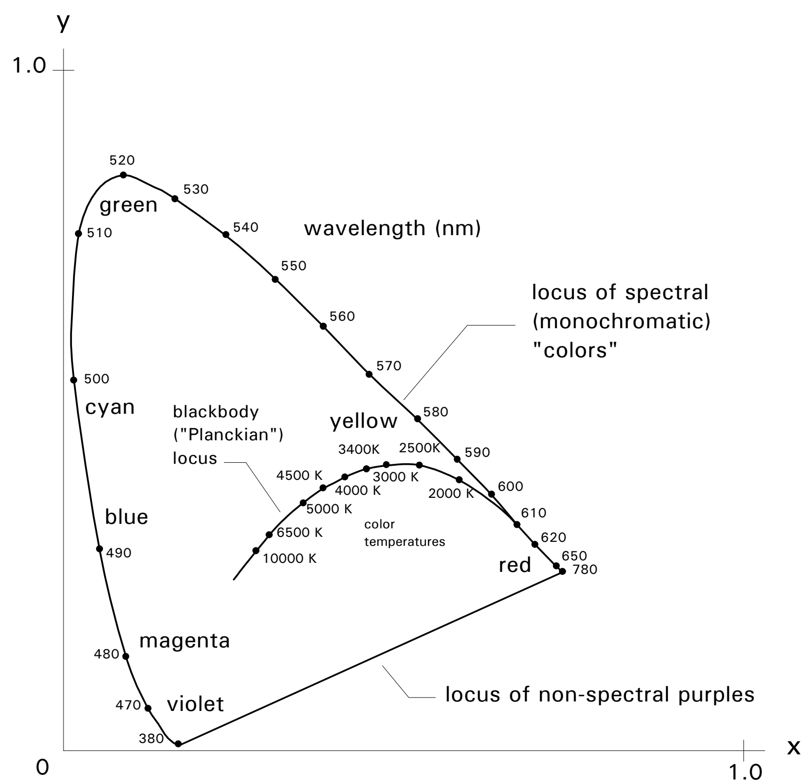

Figure 1. The blackbody locus

Correlated color temperature

Does every chromaticity have a color temperature? Strictly speaking, no. Only chromaticities falling on the Planckian locus (chromaticities that could actually be emitted by a blackbody radiator) have true color temperatures.

However, for chromaticities falling near the locus, but not on it, we may usefully state a related property called the "correlated color temperature". This is the color temperature of the point on the blackbody locus that is "closest in appearance" (chromaticity-wise) to the chromaticity of interest.

Technically, this means the point on the blackbody locus nearest the point representing the chromaticity of interest when the blackbody locus is plotted not on the familiar CIE chromaticity diagram (with coordinates x and y) but rather on the CIE Uniform Chromaticity Scale

(UCS) diagram (1960), with coordinates u and v, on which equal geometric distances represent essentially equal perceived differences in chromaticity.[7] Figure 2 shows how that works.

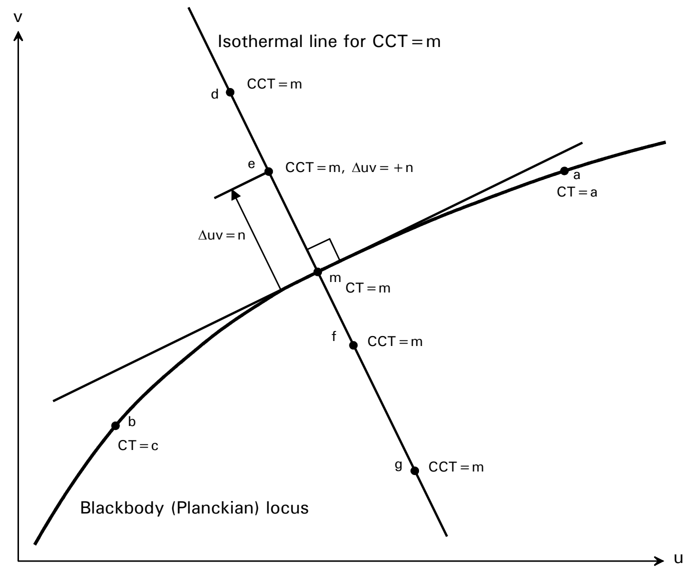

Figure 2. Planckian locus on the CIE u-v plane

The figure shows the Planckian locus on the CIE u-v plane. We have shown two arbitrary blackbody chromaticities, points **a** and **b**, whose color temperatures are also designated *a* and *b*.

Consider now point **e**, not lying on the locus, It does not have a color temperature. We would like to know, though, what point on the locus is visually closest to its chromaticity. Because of the nature of the CIE u-v plane, that will be the point on the locus that is geometrically closest to point e.

To locate that by construction, we draw a line from point **e** that intersects the locus at the point where the line is perpendicular to the locus (that is, is perpendicular to a line tangent to the locus through that point). We call that point **m**, and it is the point on the locus nearest the point **e**.

Thus, the color temperature of point **m**, which we will also call *m*, is said to be the correlated color temperature (CCT) of point **e**.

---

[7] The equivalence between distance on the diagram and perceived chromaticity difference is even more consistent on the CIE 1976 (u'-v') chromaticity diagram. Nevertheless, it is the convention to make determinations of correlated color temperature on the 1960 u-v diagram.

But note that for **any** point lying on our line—such as the points I have labeled **d**, **f**, and **g**—that is also true. Thus all of those points also have a correlated color temperature of *c*. For that reason, the line is said to be an *isothermal line* (line of constant temperature).

We can now see that when we give the CCT of a light source, we are not at all completely pinning down its chromaticity. To do that, we must add another parameter.

How far off the locus

One way to do that is to state how far from the locus (and on which side of it) does the point representing the chromaticity of interest lie. We describe that in units the same size as used for the u and v coordinates themselves, and that distance is often called "Δuv" (Δ is the upper-case Greek letter *delta*, often used to represent a difference—the notation is read "delta u v"). By convention, chromaticities above the locus have positive values of Δuv, and those below negative values.

Of course, we most often plot chromaticities not on the CIE u-v plane but rather on the CIE x-y plane—the so-called *CIE (1931) chromaticity diagram*. Because of the transformation between the u-v coordinate system and the x-y coordinate system, the Planckian locus takes on a different shape (which we saw earlier on figure 2). Additionally, the isothermal lines (we saw just one of them on figure 2) are no longer perpendicular to the locus, and the scale for Δuv changes as we move across the diagram. We see all that in figure 3:

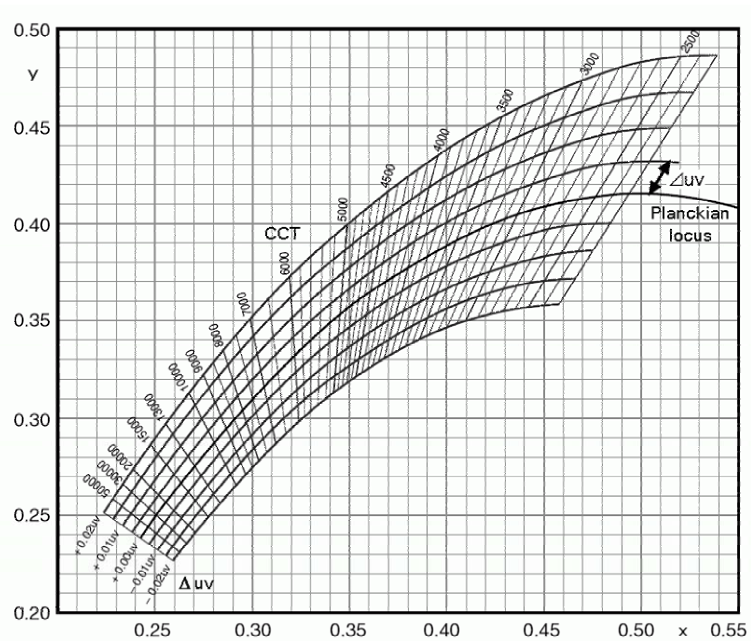

Figure 3. CCT and Δuv on the CIE x-y plane

We see the relevant part of the locus itself as well as isothermal lines for a number of values of correlated color temperature from 2500 K to 50,000 K. We also see curves of constant Δuv over the range from -0.02 to +0.02. This is about the range we encounter for chromaticities for which it is sensible to state a correlated color temperature—chromaticities that can reasonably be said to be "white" or "almost white". (We could state a correlated color temperature for, say, fully-saturated primary green, but it wouldn't be really useful.)

In some cases, the departure of the chromaticity of interest from the locus is not given in terms of Δuv but rather in terms of Δxy. That is of course the distance from the point of interest to the Planckian locus, along an isotemperature line, measured on the x-y chromaticity diagram and given in the same unit used for the x and y coordinates.

Some times a third metric is given, called ΔE. This is the distance, in the three-dimensional CIE L*a*b color space, between the chromaticity of interest and its "color temperature proxy" on the Planckian locus. The unit there is the unit of the L*, a*, and b* axes.

Some other thoughts

It is interesting to note that two standard (CIE-defined) reference illuminants, "Illuminant C" and "Illuminant D_{65}", which have different chromaticities, both have a (correlated) color temperature of 6500 K, thus reminding us of the fact that describing the chromaticity of a light source in terms of (correlated) color temperature alone is not really satisfactory.

In most cases, where a "color temperature" is stated for some light source, it is almost always the correlated color temperature that is spoken of—most of those sources, not being "Planckian", do not have e true color temperature.

PRACTICAL IMPLICATIONS

Color displays

Different designs of the tricolor displays used in color television receivers and computer displays have different properties with respect to how the colors coded in a TV transmission or a digitized graphic image will appear to an observer. Perhaps the most important property is the "white point", the chromaticity the unit exhibits when rendering a color that is coded in the signal or image file as "reference white"[8].

---

[8] Of course what that means must be described for the particular coding system involved. Often one of the standard "white" illuminants, such as illuminant D_{65}, is specified.

Often, the desired chromaticity of the white point for a given display system is stated in terms of "color temperature". Remember, however, that this is probably to be interpreted as a *correlated color temperature*. As such, it does not of itself precisely define a chromaticity—just the nearest blackbody chromaticity.

Preferred white point chromaticities for color displays are often rigorously specified in terms of a CIE-defined standard illuminant, which implies a specific chromaticity (and not just a certain correlated color temperature).

Illumination of an object

It is common to speak of the color temperature of light sources used in photography. This arises, for example, in setting the "color balance" of a digital camera or determining the appropriate color correction filter for use with a film camera. We may also hear of the color temperature of a light source in connection with planning the illumination of products on display for direct viewing. However, there can be some surprises in such usage of color temperature.

The statement of a color temperature for a light source will certainly somewhat define the chromaticity of the light as it would be seen directly by a human observer. But in the situations mentioned above we are not interested in the chromaticity of the light *per se*. We are interested in the effect of the light source on the chromaticity of the light reflected by different surfaces in the scene being observed or photographed.

Light from two different sources may exhibit the same chromaticity (and thus may be said to have the same color temperature, perhaps only in the *correlated* sense) but yet have dramatically-different spectral distributions.[9] Those different spectral distributions, interacting with the reflectance spectrum of a particular surface in a scene, can produce different spectral distributions in the reflected light, distributions which may well present as different chromaticities to a human observer. We are all familiar with this scenario: "The vest looked the same color as the trousers in the store, but not out in the daylight". (In this case the chromaticities of the two sources are likely not the same, but the phenomenon could occur even if they were, if they did not have the same spectral distribution.)

Thus, light from an incandescent lamp having a certain correlated color temperature may produce a significantly different chromaticity of the light reflected from some object it illuminates than would light

[9] This situation is referred to as *metamerism*.

from a fluorescent lamp having the identical correlated color temperature (and perhaps even an identical chromaticity).

Accordingly, placing reliance on knowledge of the color temperature of different light sources is only safe if we know that the two sources have similar spectral distributions[10], as in the case of two different types of incandescent lamp, or sunlight under different circumstances (such as at different times of the day). In particular, discharge lamps (including fluorescent lamps) often have spectral distributions greatly different in their general structure from those of a black body. Thus, expressions of color temperature (or correlated color temperature) for such lamps must be contemplated with great caution.

"White balance" in photography

In photography, we often compensate for the chromaticity of the ambient illumination in order to produce the "expected" color result in the delivered image. This may be done with the use of a filter over the lens, or (with a digital camera) by image processing either in the camera or in subsequent "post-processing" software. This is often spoken of as of obtaining proper "white balance".

In order to do so, we must either measure, or make a reasonable assumption of, the chromaticity of the light source. There are various instruments that can make such a measurement.

The more primitive instruments for measuring the chromaticity of ambient illumination for photographic color management purposes give a reading only in terms of correlated color temperature (the "correlated" rarely being mentioned in the instructions).

More sophisticated instruments report the measured chromaticity in one or more of these ways:

- in terms of the *x* and *y* coordinates of the CIE chromaticity diagram

- the correlated color temperature (usually labeled as such, in this situation!), plus Δuv (delta uv), the distance from the point of interest to the blackbody locus on the CIE u-v chromaticity diagram (in the same units as the *u* and *u* scales), or in some cases Δxy (delta xy), the distance from the point of interest to the blackbody locus on the CIE x-y chromaticity diagram (in the same units as the *x* and *y* scales).

[10] There would of course be some differences in the spectral distributions or else the two would not have different color temperatures.

Most modern digital cameras can themselves be employed to make a measurement of the chromaticity of the ambient illumination (often by fitting the lens which a translucent white diffuser disk, or by aiming at a "gray card" whose reflectance is chromaticity-neutral). In this case, the findings are not explicitly reported to the operator, but are used to set a color correction in the camera, or are reported in the camera output file such that they can be used by subsequent color correction operations.

Most modern digital cameras also have a repertoire of preset white balance chromaticities which the photographer can invoke based on a general knowledge of the nature of the ambient illumination: "full daylight", "partially-shadowed daylight", "incandescent light", "fluorescent light", "photoflash", and so forth.

Some digital cameras also allow the photographer to set an arbitrary chromaticity which is on the blackbody locus, or possibly on a similar locus called the daylight locus, by entering its color temperature. (Of course, the instructions don't usually say anything about the blackbody or other locus. They just typically say, "you can set a white balance correction in terms of color temperature".)

Often, we will see stated in the camera manual the "color temperature" of the camera's color balance presets. Of course, at best this is stating the correlated color temperature of the chromaticity upon which this preset is based. This value cannot fully describe that chromaticity (doing so would also require statement of the associated Δuv).

Misunderstanding of this matter can be quite problematical. A photographer may say, "My camera doesn't have a preset white balance for sodium streetlights, but I can set white balance by color temperature. What color temperature should I set to shoot under sodium streetlights?" It's very unlikely that any blackbody chromaticity—the only kinds that can be described "by color temperature"— would provide proper color correction for illumination by sodium streetlights.

THE UNIT "MIRED"

Various photographic calculations, especially those involving the use of color filters to compensate for the chromaticity of the light source, can be done approximately by working with correlated color temperature alone (ignoring Δuv). The important calculations all involve the reciprocal of the (correlated) color temperature (one divided by the CCT), since the effect of a certain filter on the CCT of the light passing through it very nearly works on the reciprocal of the CCT.

There is in fact a unit for the reciprocal of color temperature, the "mired" (pronounced in two syllables—"mih-red"). The name comes from "**mi**cro **re**ciprocal **d**egree" [11], and the reciprocal color temperature in mireds is 1,000,000 divided by the color temperature in K.

Thus, if we have a filter whose effect on color temperature such that light having a CCT of 4000K, if passed through the filter, comes out with a CCT of 4200K, the shift caused by the filter (in mireds) is:

$$\frac{1{,}000{,}000}{4200} - \frac{1{,}000{,}000}{4000} = -236\,\text{mireds}$$

Thus that filter can be said to give a color temperature shift of -236 mireds. That shift (as we can see from the example) is in the direction of increasing CCT (in the "bluer" direction).

Sometimes the rating of a filter in this way is given in "decamireds" (a unit that corresponds to 10 mireds). The value above would be given as "-23.6 decamireds".

Recently, the name "reciprocal megakelvin" (symbol: MK^{-1}) has come into use for this same unit.[12] (The definition is identical.) Among other advantages, it eliminates the implied reference to the "degree Kelvin", a unit name that is no longer used.

#

[11] The "degree" referred to is of course the "degree Kelvin", a unit name that is no longer used.

[12] It is the standard unit under the International System of Units (SI).