BY MIKE WOOD

Photopic curves—the old and the new

This article continues and extends my Winter 2008 article in Protocol *on the CIE photopic curve. We now have a partial solution to the problems raised then. Some of the earlier material is repeated here for ease of reading. I'm allowed to plagiarize myself!*

PHOTOMETRICS IS A STRANGE BRANCH of physics measurement science. Unlike most other measurements that have an absolute reference, such as a kilogram for mass, or a meter for length, which everyone can point to, touch, and agree on, photometrics doesn't. Instead everything is referenced through the responses of a hypothetical *ideal observer* and seeks to report what the average human eye would see.

It is possible to measure light in absolute units such as watts; we call those measurements radiometric rather than photometric. However radiometric measurements tell us about photons and energy, but nothing about perception or how the eye and brain interprets those photons. Instead, readings of the output of a light in photometric units such as lux, footcandles, or lumens are all based on the theoretical response of the standard human eye and brain, and, as such, are really statistical results that include elements of psychology as much as they do physiology and physics.

For example, a luminaire can emit as much energy as you want in the infrared or ultra-violet regions of the spectrum but, if we can't see it with our eyes, then by definition it has zero light output! An infrared or ultraviolet source has a power output measurable in watts, but no light output measurable in lumens. Moreover, most early testing of the human eye was based on the assumption that the light source has a continuous spectrum, similar to that from an incandescent light or the sun. Even today, just about every modern light meter was designed with this assumption.

Color matching functions

I'm sure you are at least somewhat familiar with the curves shown in **Figure 1**.

These are the CIE 1931 Color Matching Functions (CMF) and represent a way of modeling human vision. They don't directly show the response of the human eye receptors to red, green, and blue (or long, medium, and short wavelength) radiation, but instead show a mathematical system that seeks to model the human eye and brain. The actual cone receptors in the eye have very different responses to those shown here. This is more what it looks like after the retina and the brain have

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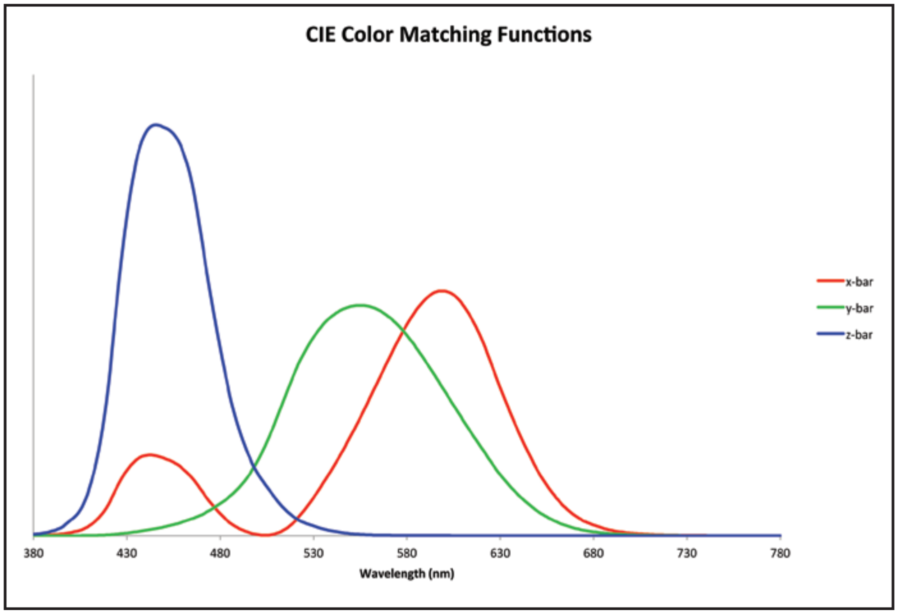

Figure 1 – CIE 1931 Color Matching Functions

processed the raw sensor information. The green curve in this diagram, labeled the y-bar value, is also the model curve that is used to represent the human eye's response to brightness information alone: That is how dark or bright a light source is with no respect to its color. This response of the light adapted human eye to brightness as it varies with wavelength is called the photopic luminosity function, or, more commonly, the photopic curve. In 1931 the data used for the photopic curve to create these CMF came from a study published in 1924 by the CIE, the Commission Internationale de l´Éclairage. (*The corresponding curve for a dark-adapted eye is called the scotopic curve, but that's not relevant to this discussion.*)

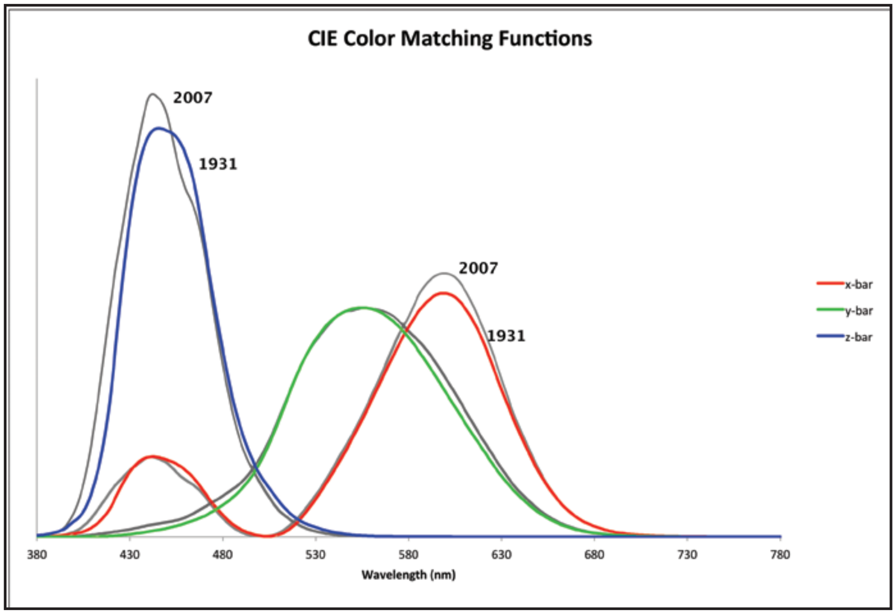

Figure 2 – CIE 2007 Color Matching Functions

Photopic curve

The 1924 photopic luminosity function V(λ) was derived from statistical surveys, primarily of college students who were predominantly male, and was published by the CIE as an international standard. It represents the normalized level of response of the human eye in well-lit conditions to different wavelengths of light. We've used that 1924 curve ever since, and just about every instrument and light meter on the planet is manufactured to the 1924 standard. Standards are great, so all should be fine, right? However, here's what the seminal work on photometry and colorimetry, *Color Science* by Wyszecki and Stiles has to say about this curve:

> **"Why have we let this clearly flawed standard remain in use so long?"**

"The standard photopic luminosity function is based on a curious combination of luminosity data from several sources and obtained by several methods. The uncertainty surrounding it is illustrated by the fact that the values from the different studies that were averaged to define it diverged by as much as a factor of ten in the violet. The function seriously underestimates sensitivity at short wavelengths."

Not only was it a poor statistical study (predominantly young male observers, which may have little to do with how women, children, or older men see light), but it seems that some of the methodology was flawed as well. It was a hard test to carry out in 1924, and it's a hard test now. How do you measure and report how bright a red light appears when you compare it to a green one and ignore the effect of color? Also, back in 1924, creating controllable narrow-band light at extreme blue or extreme red wavelengths wasn't a simple task. Why have we let this clearly flawed standard remain in use so long? It's 90 years this year since this was published; surely we could do better with the testing and the statistics today!

Yes, it's true, we can do better today. However, until recently, it hasn't really mattered that the 1924 study was flawed. The CIE 1924 photopic curve and light meters that use it are perfectly adequate with continuous spectrum light sources and give you answers within a very few percent of each other. Thus, none of this matters much with an incandescent source that is continuous and has almost no light in the blue or violet anyway. Bring narrow-band LED emitters into the picture though, and it's a different story.

Narrow-band emitters

As I reported in the 2008 article, I discovered that I was getting measurements from my various light meters that varied enormously when trying to measure LED-based luminaire, particularly those that used a mix of colored emitters such as RGB. These errors aren't small either; in some cases I've seen differences of 10x or more between meters when measuring a blue LED. The reasons for this are twofold: firstly, the CIE 1924 curve dramatically underrepresents how much light we can see in the deep blue, and secondly, because the meter thinks this blue light is almost invisible, errors in the meter can be very high in this region. Any light source with a discontinuous spectrum that has a high component in the blue end of the spectrum exhibits this problem to some extent. For example, you get the same problem with Congo Blue gel. Congo Blue always looks brighter on stage than the very low transmission figure in the swatch book would suggest. It also looks brighter to our eye than the light meter tells us.

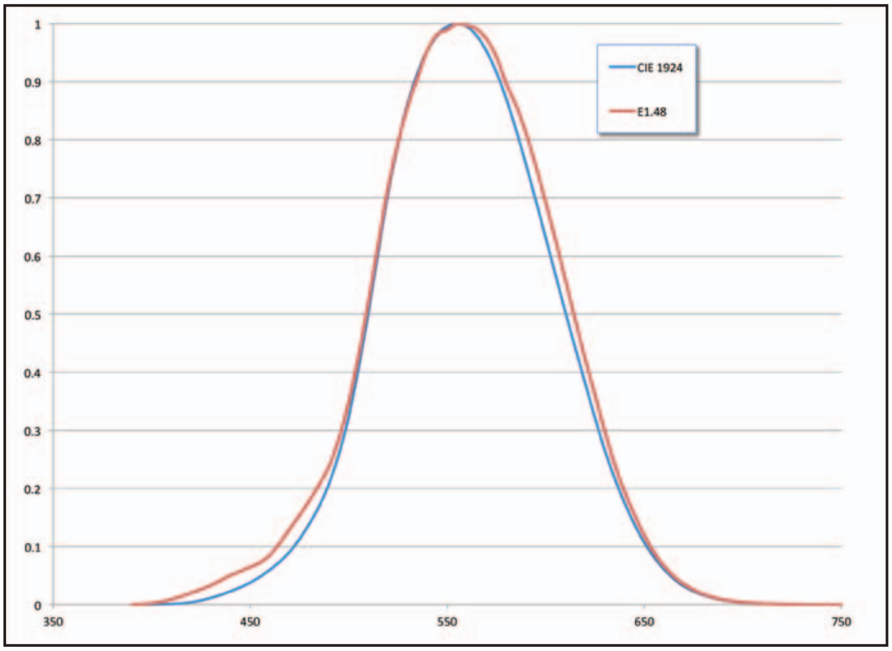

Figure 3 – Luminous Efficiency Functions CIE 1924 and E1.48

Improved photopic curves

Figure 2 shows a new set of CMF curves, this time from 2007, overlaid on the original 1931 CMF.

You can see that this later set of functions recognizes changes in all three curves from 1931. In particular our vision in blue and red is more sensitive than first thought, and also we can see further into the deep blue than was believed. There have been many, many proposed versions of the photopic curve V(λ) over the years, all showing significant changes from the old established 1924 version. Most recently, a team of researchers has established a new proposal that combines many of the most recent studies and links them back to known physiological structures in the eye. This curve is scheduled to be adopted by the CIE as CIE 2012, and is the curve embodied in *ANSI E1.48 – 2014, A Recommended Luminous Efficiency Function for Stage and Studio Luminaire Photometry*. **Figure 3** shows the E1.48 curve compared with the 1924 version.

You can see that vision in blue is significantly better than before. A monochromatic blue light at 450 nm would measure twice as bright using the new curve compared to the old. This more closely represents what we actually see; deep blue LEDs and Congo Blue are perfectly visible.

How much difference does it make?

Fine, you might say, but isn't this just of academic interest? How much difference does this make in the real world? The answer is, quite a lot, and not only with deep blue LEDs. **Figures 4 – 7** show examples of real light sources that I measured myself and demonstrate how they would be reported, in terms of lumens, lux, or footcandles under the old and new curves.

Not much difference for a green LED, where *ANSI E1.48* reports only 2% more than CIE 1924, that's within the tolerance of the meter and irrelevant. However, red is 11% higher using the new standard, and blue is a very significant 47% higher. That's not academic, that's real lumens that your eye can see that are being dramatically underreported. Even white LEDs that use a blue pump and a yellow phosphor are affected and can give results 10% higher with *E1.48*. Remember it isn't that anything has changed with your eye or the LEDs; it's just that the older CIE curve, and any light meter that uses it, underreports blue. It's a symptom of photometrics not being an exact science and having to rely on an inevitably flawed mathematical model of the average human eye. Radiometrically LEDs read the same in watts as they always did. No photopic curve is needed. Watts are absolute; lumens (which are the photometric equivalent of watts) are not.

How do I use *E1.48*?

It's unrealistic to expect that light meter manufactures will suddenly switch to using CIE 2012 / *ANSI E1.48* for their photopic curve. There have been many versions since the original curve was published in 1924, and the market didn't switch to any of those, so why should they change now? The truth is that for 99.9% of the world lighting market, the errors in CIE 1924 are of limited interest. The entire lighting world, apart from us, uses white light almost exclusively, and the differences when measuring white light are small. However, in entertainment lighting we use colored light all the time, and a 2:1 difference in the brightness of a blue light is very significant.

I hope that, with digital light meters, we will see an option to choose the V(λ) curve we want to use. It would be trivial to add the calculation, but I'm not holding my breath. More realistically, we have a couple of real options. Using a spectrometer you can measure the radiometric output of a light, and then apply the V(λ) curve mathematically. It's a simple process in Excel. Of course, using a spectrometer is not quite so convenient as using a light meter, but small portable spectrometers are appearing on the market that make this task very much easier. **Figure 8** shows an example of the one I use. Secondly, and most importantly, we should be asking that the lighting manufacturers report photometrics for their products, particularly SSL products, using the *ANSI E1.48* V(λ) curve. They will be using a spectrometer anyway, so shouldn't have any real problem in providing the data.

Whatever happens, it's clear that probably we will have to live with CIE 1924, at least for a few more years, but we should do so with care and with an educated eye. Whenever we use a light meter that uses the CIE 1924 curve for a narrow bandwidth light emitter like a saturated color LED,

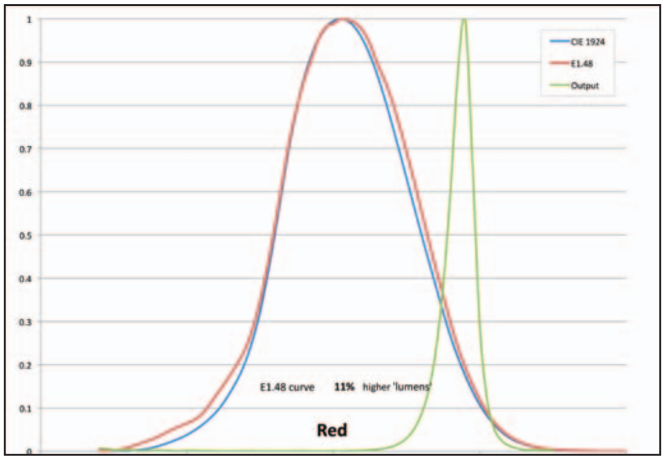

Figure 4 – Comparison with red LED

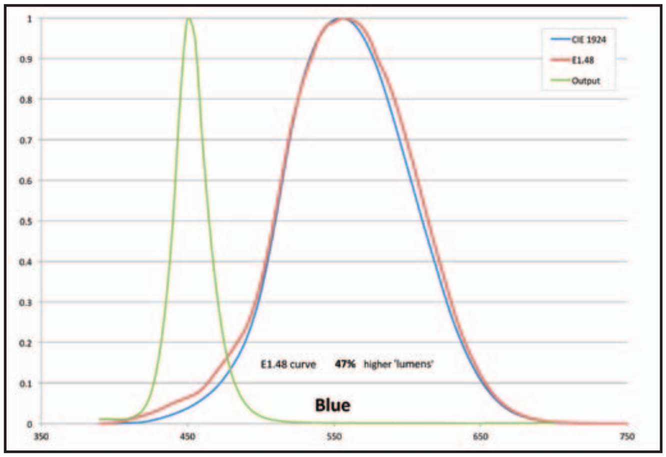

Figure 6 – Comparison with blue LED

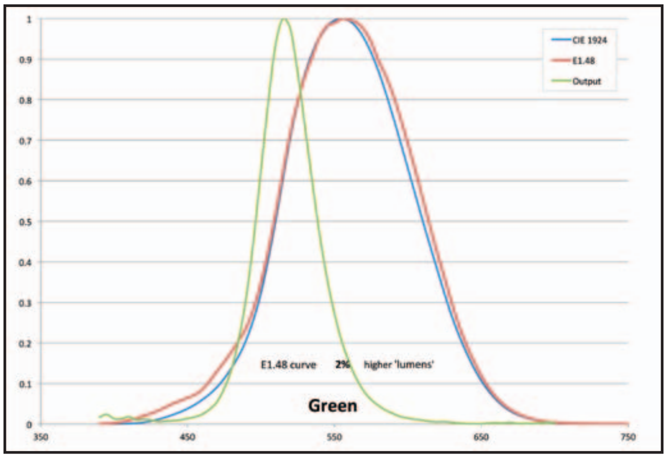

Figure 5 – Comparison with green LED

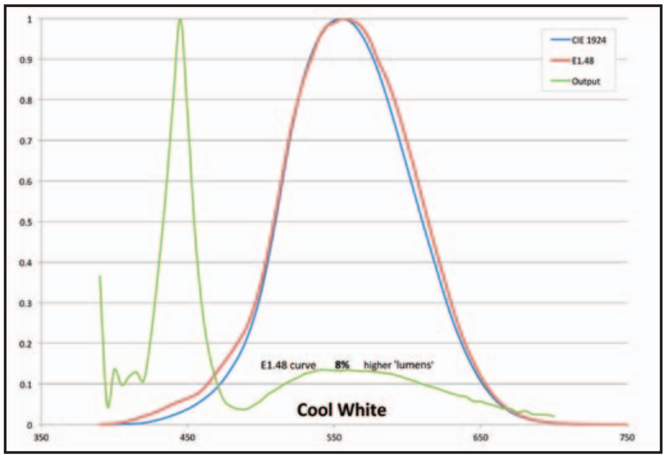

Figure 7 – Comparison with phosphor white LED

particularly one in the deep blue, we need to be aware that the meter is under-reading, perhaps significantly. Photometrics, as we've stated repeatedly, is not an absolute science, but using *ANSI E1.48* as the meter curve would significantly reduce the problem. ■

Mike Wood runs Mike Wood Consulting LLC, which provides consulting support to companies within the entertainment industry on product design, technology strategy, R&D, standards, and Intellectual Property. A 35-year veteran of the entertainment technology industry, Mike is the Immediate Past Chair of the PLASA Governing Body and Co-Chair of the Technical Standards Council. Mike can be reached at mike@mikewoodconsulting.com.

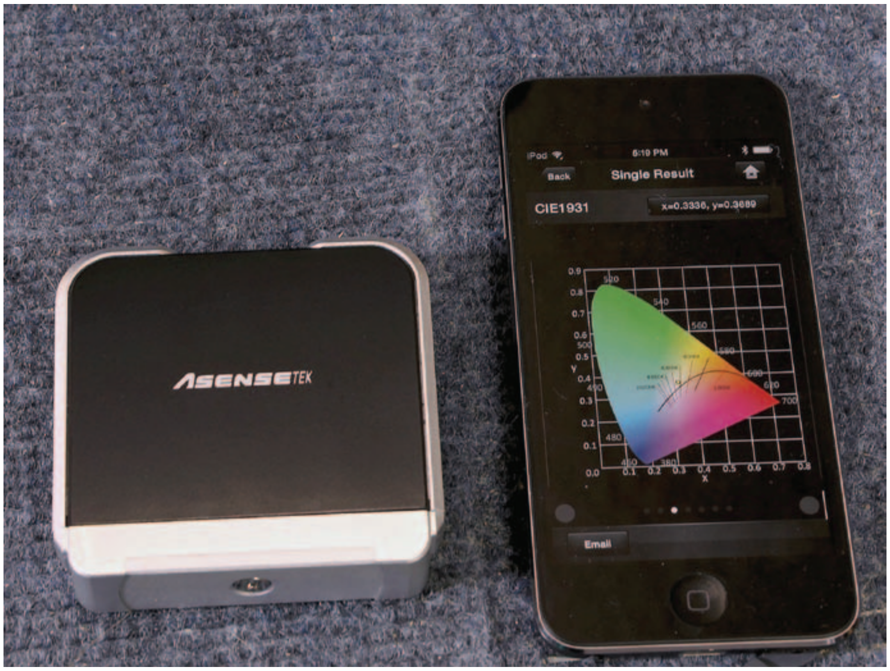

Figure 8 – Portable spectrometer