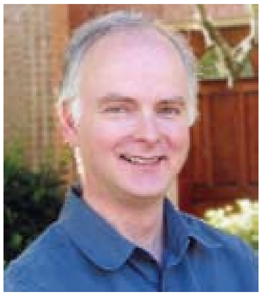
BY **MIKE WOOD**



# When white light isn't white

WHITE LIGHT IS WHITE LIGHT ISN'T IT? In the field of entertainment lighting we've long known that isn't true and that white can actually mean a broad range of colors a bit like those 27 shades of white you see in paint charts. Still, in the main, dealing with the differences has been a relatively simple one-dimensional problem. With the rapid expansion of LEDs as viable light sources all that is changing.

Why do I say it's been a one-dimensional problem? Well, the light source that is still by far the most commonly used in entertainment lighting is the incandescent lamp and an incandescent lamp filament emits radiation in a completely continuous spectrum. As the tungsten filament is heated from its cold, black state it changes color in a familiar manner passing through red, orange, yellow and white before finally reaching a bluish-white just before it melts. The color of light emitted by a hypothetical, perfect incandescent black body depends only on its temperature and the color of light produced will always lie somewhere along the Planckian locus (often called the black body line) on a color chart. We use the position along this locus to describe the color of a white light source and refer to that position, measured in Kelvin (K), as its Color Temperature.

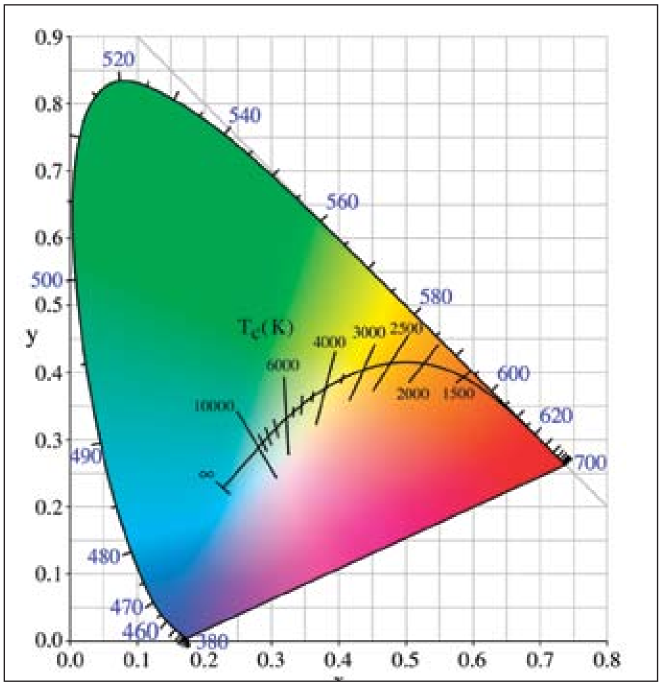



**Figure 1** illustrates the Planckian locus on the familiar 1931 CIE chromaticity chart with approximate color temperatures (Tc) marked. The position along that curve is the single value that I have been referring to as the one-dimensional problem.

When we say a lamp has a color temperature of 3200K, we mean that a metal heated to a temperature of 3200K would produce light of about the same color as the lamp. If that same metal is heated to 3700K, it will produce a bluer light. 3700K is pretty much as high as you can go with tungsten as that's close to its melting point (the highest of any metal). Entertainment incandescent lamps are typically in the 2500K to 3200K range where the filament is a little cooler and more robust. Natural daylight, which is also very close to a black body source, has a color temperature which can be anything upwards of 6000K depending on how high the sun is in the sky and how overcast that sky is. Direct sunlight alone, without the contribution from the blue sky and the diffusion from clouds, is a little lower at around 5300K. For normal lighting purposes we often average these out such that the term *daylight* commonly refers to a color temperature of 5600K.

## The second-dimension—correlated color temperature

Another group of lamps with which we are very familiar are High Intensity Discharge lamps (HID) such as HMI, MSR, and MSD. These lamps have discontinuous spectra and, although the manufacturers strive to get close, their output color points don't usually fall exactly on the Planckian locus. However those color points are usually close enough to the locus that we can use the concept of correlated color temperature where the correlated color temperature (Tc or CCT) of a source is defined as the temperature of the Planckian radiator whose perceived color most closely resembles that of the source.

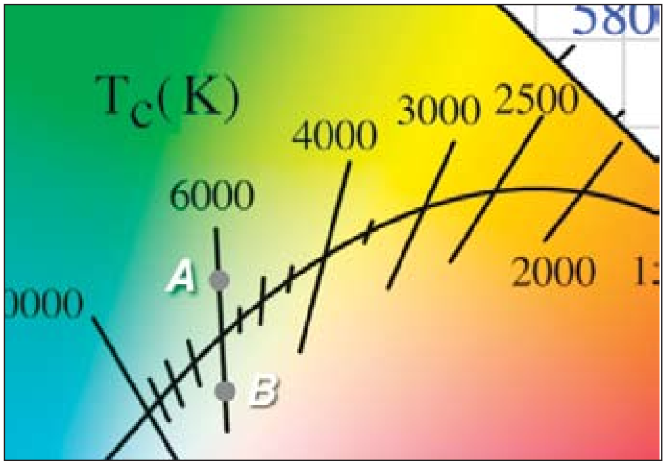



**Figure 2 – Correlated Color Temperature**

This is an approximation of course but one that works well in practice. In **Figure 2** the lines of equal correlated color temperatures are the short lines crossing the Planckian locus and points A and B are both on the 6000K line. Once we are back on the Planckian locus then we can use our earlier definitions and treat the source as if it were a black body radiator and we can be comfortable with using gels to correct color temperature up and down the Planckian locus to increase (CTB) or decrease (CTO) the color temperature.

**“How much color variation are we prepared to accept between similar whites?”**

The use of correlated color temperature isn't the whole story though, especially if the color coordinates are a long way from the Planckian locus. You can see from **Figure 2** that two lamps (shown as points A and B) whose color co-ordinates fall either side of the Planckian locus, one above and one below, could have the same correlated color temperature but still look very different. One, A, would appear greenish and the other, B, slightly magenta or pinkish. It's not uncommon to see this problem with discharge lamps used in followspots or automated lights and TV and film practitioners are very familiar with using “minus green” gels to try and correct the problem. A green tint in what is supposed to be white light is usually to be avoided at all costs, our eyes are particularly sensitive to green and it makes skin tones in particular look very unnatural. If there has to be an error it is usually better for a light source to err on the magenta side than the green one.

This green correction is a second-dimension of correction and, although we know about it, unless you are working in the television or film areas of our industry and using large HID lamps, it's not something we are dealing with every day. However the almost inevitable takeover by LEDs as the ubiquitous light source for the 21st century will force us to deal with this problem all the time.

## My LED is white, but what about yours?

Like HID sources LEDs give us a discontinuous spectrum, and often one with even bigger gaps. This is particularly obvious when using an LED luminaire which uses a mix of red, green and blue emitters to produce a white; but is also the case when using so called white LEDs. Currently there are two common techniques for producing white LEDs. The first technique just mimics the RGB luminaire and uses multiple wavelengths of different LED dies mounted in a single package to mix an approximation to white light, while the second uses a deep blue (InGaN) or UV (GaN) LED die with a phosphor coating to create white light. The phosphor technique is becoming very common and is now pretty much the norm for white LEDs. The development and manufacture of these phosphors owes a lot to the R&D done on the similar phosphors used in fluorescent lamps and, although they are getting better every day, they suffer from many of the same problems with gaps in the spectra and a propensity to appear green.

Whichever way you make white light from your LEDs you now not only have to worry about the first-dimension of correlated color temperature but also the second-dimension of green/magenta shift. To make matters worse the manufacture of these LEDs is an inexact science with a wide variation in the product coming off a single production line. The LED manufacturers deal with this by *binning* where they measure the output of the LEDs and sort them into various ranges, or bins, before sale. The size of each of those bins and the subsequent range of colors each one encompasses is critical in determining how close a match the LEDs we use in our lights will have to each other and thus how much color variation we are going to see between units.

We now have to ask ourselves a question. If we can't have an exact match, how much color variation are we prepared to accept between similar white LEDs? It's a question with more than one answer depending on what you are lighting and how. This question has been extensively studied with fluorescent lamps and there is now an ANSI standard (*NEMA ANSLG C78.377-2008, Specifications for the Chromaticity of Solid State Lighting Products for Electric Lamps*) recommending a series of bins based on 7-step MacAdam ellipses as the color-tolerance criterion for solid state lighting—that's a huge variance! The standard also discusses perhaps tightening this to a 4-step ellipse in the future but, although better than 7, that's not too tight a tolerance either. A single step MacAdam ellipse represents a region plotted on a color space diagram showing where colors are perceived to be the same by the average viewer and, logically, a 4-step ellipse is four times larger—in other words a color difference that is four times more than the minimum color difference we can see. But what should we use for LEDs? Just because a standard works (somewhat) for fluorescent lamps doesn't mean it works for LEDs. As an example the red ellipse plotted in **Figure 3** illustrates approximately what a 4-step MacAdam ellipse looks like on the CIE chart. Any sources within that ellipse would be classified as being the same color.

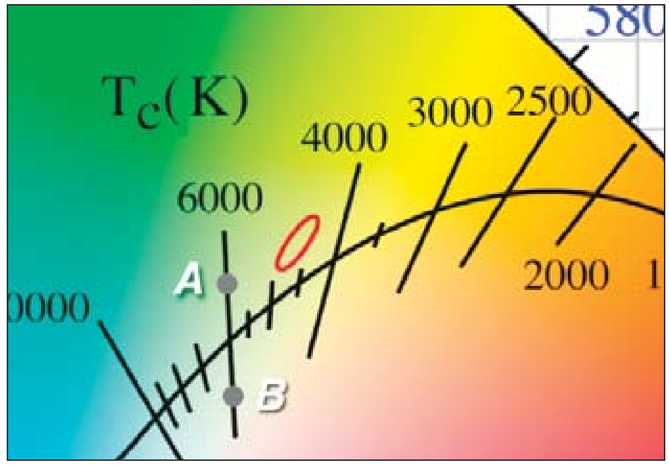



**Figure 3 – MacAdam Ellipse**

## The LRC study

Establishing these criteria is not a simple task—we are dealing with human perception and all the natural variation that implies. The Lighting Research Center of the Rensselaer Polytechnic Institute has taken on the task and recently published preliminary results on a study to determine these criteria and reported as follows (text extracts quoted with permission from LRC). In the study, LRC researchers conducted experiments to develop

> **"Green is great for efficiency but awful for skin tones . . ."**

color-tolerance criteria for white LEDs. The criteria define at what point a normal human observer would see a just-noticeable color difference between LED light sources. Their study also investigated the impact of light level, spectrum, correlated color temperature (CCT), and visual complexity of the illuminated scene on the color tolerance range. This information was then used to establish recommended color-binning criteria for white LEDs. As an example of currently available binning, **Figure 4** shows the white color-binning currently offered by Lumileds for its Luxeon emitters, these bin sizes vary between four and six step MacAdam ellipses. Is this good enough?

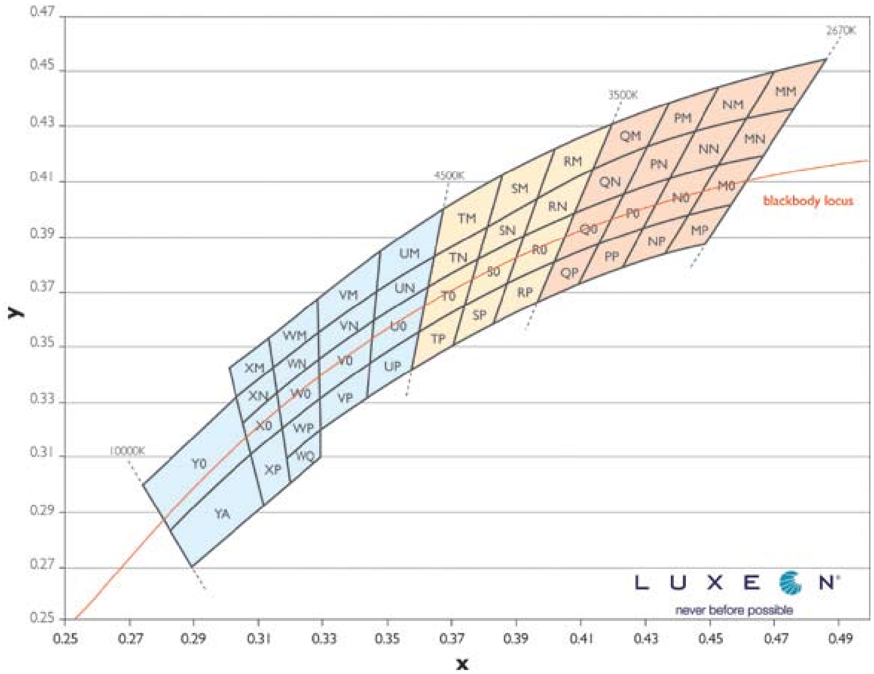



Figure 4 – Luxeon binning

To carry out the tests LRC researchers built a display cabinet with two side-by-side compartments. Using RGB LED panels, MR16 halogen lamps with RGB filters, and a variety of white and multicolored backgrounds, test subjects compared the color of white light in one compartment against the other. The reference compartment showed a constant white light color at a specific x, y chromaticity value. This same value was used as the starting point for the adjacent test compartment light source. The test compartment then changed color systematically in incremental steps. At each step, subjects were asked whether they saw a color match or noticed a color difference. If subjects saw a color difference, they commented on how different the two compartments appeared.

As might be expected the type of visual background has a major impact on the color tolerance range. Complex visual backgrounds using different colors allow for much greater variations in white light color before we notice a color difference than a plain white background. Taking all this into account, LRC proposed the following two criteria for color binning white LEDs:

- **2-step MacAdam ellipse**—For applications where the white LEDs (or white LED fixtures) are placed side-by-side and are directly visible, or when these fixtures are used to illuminate an achromatic (white) scene. Accent lighting a white wall and lighting a white cove are some examples.
- **4-step MacAdam ellipse**—For applications where the white LEDs (or white LED fixtures) are not directly visible, or when these fixtures are used to illuminate a visually complex, multicolored scene. Lighting a display case and accent lighting multicolored objects or paintings are some examples.

LRC were not specifically considering entertainment lighting of course but I would argue that, for many of our applications particularly when lighting critical skin tones, we fall in the first category and should be looking at 2-step MacAdam ellipses. Until very recently this was a much tighter tolerance than the binning offered by the major LED manufacturers; however the LED manufacturers are responding with moves in the right direction and Osram recently announced a new initiative to move to 3-step binning for white LEDs which they claim is the finest binning in the industry. If this

> **"Color consistency will become a major concern, if not a headache, for us all."**

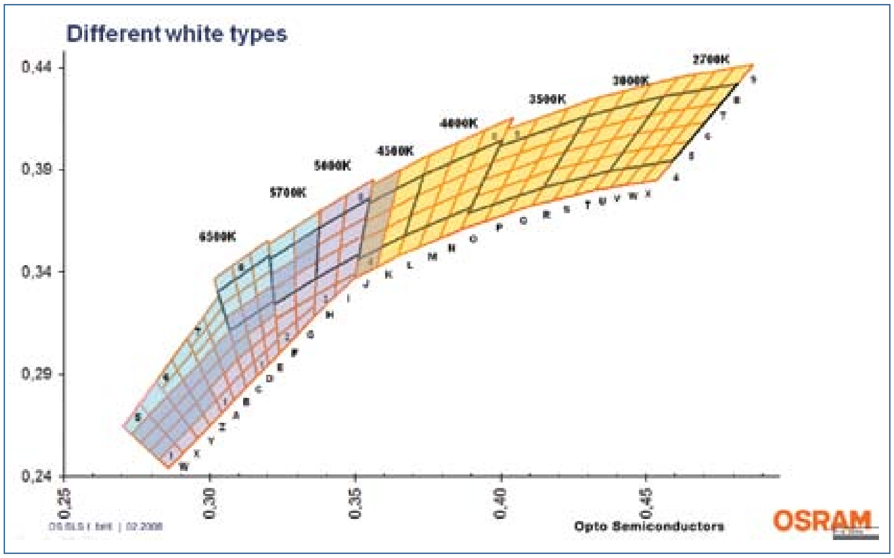



Figure 5 – Osram "Fine White" binning

initiative is successful I'm sure the other manufacturers will follow and perhaps improve even more.

**Figure 5** shows the proposed Osram binning structure superimposed on the eight rectangular bins (black quadrilaterals) recommended in NEMA ANSLG C78.377-2008 and shows just how big those bins are. You can also see from **Figure 4** just how many of those bins are on the green side of the Planckian locus. As discussed earlier, whatever we *do* want in a white LED the one thing we *don't* want is green—errors on the magenta side of the locus are always more acceptable to the eye than errors on the green side. Unfortunately the phosphors used for white LEDs, like those used for fluorescents, tend to be most efficient on the green side so that's where the manufacturers like to be as it gives the most lumens per watt! Green is great for efficiency but awful for skin tones….

Only a year ago the use of LEDs in entertainment lighting was pretty much restricted to direct view and display applications and for lighting backings and set pieces, much of the time in deep colors, so none of this was of concern. Now LEDs are bright enough to be used to light performers and to be used as a white light source, color consistency will become a major concern, if not a headache, for us all. We have been accustomed to not having to worry about it with incandescent lamps so the question isn't usually in the forefront of our minds. Time to learn about that second-dimension!

*Thanks to the Lighting Research Center of the Rensselaer Polytechnic Institute, Troy, NY for permission to quote extracts from their research which was sponsored by the Alliance for Solid-State Illumination Systems and Technologies (ASSIST).* ■

**Mike Wood** is President of Mike Wood Consulting LLC which provides consulting support to companies within the entertainment industry on technology strategy, R&D, standards, and Intellectual Property. A 30-year veteran of the entertainment technology industry, Mike is the Treasurer and Immediate Past President of ESTA.

BY MIKE WOOD

# When white light isn't white—Part 2

LAST ISSUE WE TALKED ABOUT WHITE LIGHT from LEDs and how *white* might mean different things at different times with different LEDs. In particular we concentrated on broadband white emitters that use a deep blue or UV LED die with a phosphor coating to create white light, but also talked about the white produced by a combination of red, green and blue (RGB) emitters. In this issue I want to expand on the topic a bit further and look at what happens when you dim those same LEDs.

Up until recently what happened when you dim an LED wasn't much of a concern—they often weren't really bright enough so we were nearly always using them at full power anyway. Also, as we discussed last time, the major use was as effects lighting in mid to saturated colors where any color shift when dimming was rarely noticeable. However, we are now starting to use these sources as white light to illuminate performers where our needs are much more critical. In the last year or so we've seen TV news studios using fully white LED lighting rigs for all their lighting, including key and fill lights on the newscasters. They still aren't really dimming them much, but that day is close at hand.

> "It's faces that matter and where we make our decisions . . ."

We are all very familiar with what happens when you dim an incandescent lamp. As the filament power is reduced it cools and emits less light, that cooling also means the color shifts towards the red end of the spectrum. The color point always remains on the Planckian locus (black body line) but at a lower color temperature. This color shift seems very natural to us; partly I think because it's what we have grown up with since Edison & Swan (I'm not getting into the discussion of which it was!) introduced incandescent lamps, but also at a more fundamental level because it's what you see in nature. What happens when the sun goes down at dusk? The sky gets redder. Throw a log on the fire and you see the colors of incandescence as the wood and ash heat up and burn with that familiar shift from black to red, through orange, and on to yellow. Coal burning in a furnace gets hotter still, and almost gets to a whitish incandescence. Whatever the reason I believe this color shift is very deeply ingrained in the human perception system and looks *natural*. As a lamp changes color along the Planckian locus we see the color is changing but we accept it and unconsciously allow for it.

**Figure 1** shows the same scene with different colors of illumination but I hope you'll agree that both appear completely natural.

**Figure 1 – Warm and cool light**

On the right hand side is the picture as it was taken in daylight where the colors are cool. That on the left simulates the same shot later in the day as the sun is setting. Much warmer color tones but it doesn't look wrong, our brain is quite happy to accept either of these as correct. It's faces that matter and where we make our decisions—if faces look right then we are quite happy with everything else. If you take a close up on a part of the photo then the difference is more pronounced and the color difference much more obvious.

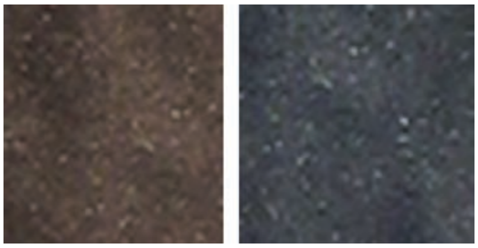


**Figure 2 – The same color?**

This is what's going on when we dim an incandescent lamp on stage. The color changes, but in a way we are comfortable with. Would it be better if it didn't change? Possibly—but if it didn't would we end up having to put the color shift back in to make the scene look natural? At least that way it would be under the control of the lighting designer.

The other light sources we are very familiar with for entertainment use are high intensity discharge (HID) lamps such as HMI, MSR, Xenon and so on. It's very common for these to be dimmed in an optical or mechanical fashion where an iris or other mechanism progressively cuts out more and more light. This gives dimming without color change and, again, we know about it and use it appropriately. For example I think a dim with no color change is entirely appropriate for a fade to black on a follow spot—a follow spot dimming isn't a naturally occurring event and we know it. It's more important that the audience's attention isn't distracted from looking at the performer, so a smooth color-change-free fade works well. Similarly, it's often true that a fade on a moving light being used as an effects projector should be color-change-free.

The problem comes when we try and mix these technologies and tasks. It's become increasingly common to use moving lights to augment the conventional luminaires on a stage not just as effects lights, but also as key or modeling lights on performers. Now if we try and dim the entire composite scene we get a conflict—the incandescent lights get redder while the moving lights don't. That conflict can jar and change the whole appearance and emphasis of the scene.  Depending on the overall brightness ratio of the two lamp types your beautifully balanced scene suddenly tilts one way or the other; the incandescent lights might look unnaturally red or the moving lights chillingly blue. The designer can compensate by subtly tweaking the color mixing of the moving lights if they have the facility, but the result isn't always as planned.

All this is by way of a preamble to set the scene for our LED discussion. The problem when we dim LEDs is that pretty much anything might happen. Depending on which type of LED technology is being used, and what dimming method, the color point may rise, may fall, may stay the same or may even go off sideways!

There are two (at least) types of dimming used for LED based luminaires. The most common is PWM (Pulse Width Modulation) dimming where the LED is switched from full on to full off very rapidly. This switching happens so quickly and at such a high rate that the eye doesn't see the transitions and integrates the individual flashes into what appears to be a continuously illuminated light. The amount of time the LED is on relative to the time it's off determines the apparent brightness. This is a very efficient means of dimming as the driver electronics are always operating at full on or full off rather than in the "in between" area where semiconductor devices can be very lossy. There is another way of dimming LEDs, however, where we directly control the current value in an analog manner so the current smoothly rises as we fade up the LED. The relationship between current and light output isn't a linear one but the technique works and is very controllable.

> **"... your beautifully balanced scene suddenly tilts one way or the other; the incandescent lights might look unnaturally red or the moving lights chillingly blue."**

What's perhaps odd is that the color point of an LED when it's being dimmed differs between these two techniques. Once you realize that LEDs have a highly non-linear relationship between both voltage and current and current and light output, and that the color changes both with current and with temperature then this perhaps isn't quite so odd.

When an LED is run from a PWM signal it only ever sees two current values; zero and full. That means that the color point when the LED is at full current is the only color point we ever see. When it's at the zero part of the PWM cycle there's no light output anyway! However when you run that same LED from a varying current source then the LED sees all the intermediate current values and its color point varies as the current changes. In both cases there's also a change of color with temperature. However that tends to be the same for both dimming systems as the temperature is dependent on the average power consumed by the LED which, within reason, will be the same in both cases.

To try and make this clearer—imagine an extreme case where the color of a hypothetical LED varies from blue at low currents up to red at high currents. If you run it with a PWM signal then either it's running at the high current, red, end or it's off; nothing else is possible. What you have in this case is a rapidly flashing red light. Now consider that same hypothetical LED running off a current source, this time as you dim it will move from red towards the blue changing color all the time as the current changes.

To complicate things further, different types and colors of LEDs also have different non-linear behavior. For example red, green and blue LEDs all dim differently, and have different temperature dependencies. Add in the phosphors for white LEDs and things get really complicated! In just our simple case restricted to two methods of dimming we have four possible scenarios; PWM dimming with phosphor white LEDS or RGB LEDs and current dimming with both types of LEDs, and they all behave differently!

The phosphor white LEDs where the white is produced by using a blue/UV LED plus phosphor exhibit the smallest overall shift in color as dimmed. This isn't too surprising as the light emitted by phosphor (usually around the yellow wavelengths) isn't significantly affected by all the changes—it's the blue LED die itself that changes and exhibits the non-linearity.

So let's look at those white LEDs first. According to research done at the Lighting Research Center of Rensselaer Polytechnic Institute$_{(Ref\ 1)}$ dimming a phosphor coated white LED using PWM from 100% down to 3% resulted in a very small color shift of around the size of a 2-step MacAdam ellipse, small enough that it likely wouldn't be noticed. What shift occurred moved the color point towards shorter wavelengths—i.e. towards the blue.

It was a completely different story though when exactly the same LED was dimmed using current source dimming. This time the color point shifted by a very noticeable amount; more than the size of a 4-step MacAdam ellipse and around three times the shift that PWM caused. That's a very visible change and one that most people would notice, particularly if a dimmed LED and an undimmed one were viewed side by side. What's even odder and counter-intuitive (at least to me) is that the shift using current source dimming is in the *opposite* direction from that seen when using PWM dimming. The source color point moves in a direction that decreases its effective color temperature and, more worryingly, moves it towards the green area of the CIE chart.

*Note: We've talked about MacAdam ellipses in earlier articles—specifically in the last issue where we discussed LED binning. A single step MacAdam ellipse represents a region plotted on a color space diagram showing where colors are perceived to be the same by the average viewer. Thus a 4-step ellipse is four times larger—in other words a color difference that is four times more than the minimum color difference we can see.*

Both these color shifts pale into insignificance however once we start looking at dimming a white source produced using RGB LEDs. **Figure 3** shows the big picture on the CIE chart.

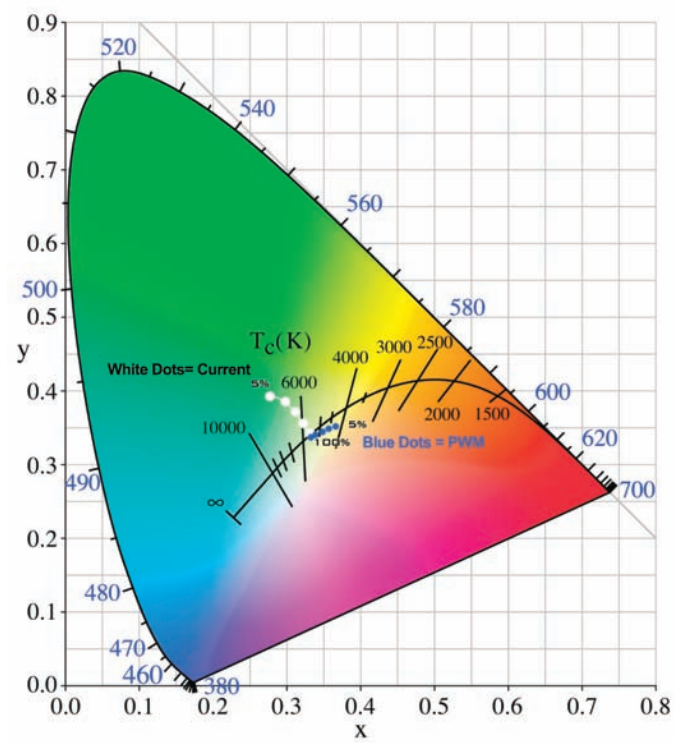



**Figure 3 – Dimming color shift for a White source using RGB LEDs**

The blue dots on **Figure 3** show how the color point of an RGB combination moves as it's dimmed using PWM. At 100% output it emits light with a color temperature just less than 6000 K and a color point close to the Planckian locus. As the power is reduced by PWM dimming the three colors equally the color point shifts to the right, or lower color temperature, keeping fairly close to the locus and ends up with a correlated color temperature (CCT) of about 4000 K when dimmed down to 5%. This is familiar behavior somewhat similar to an incandescent source, albeit a smaller shift over that range. I would imagine that this shift looks fairly natural to the eye.

Current source dimming those same LEDs gives us completely different results. Look at the white dots on **Figure 3,** they start out at just under 6000 K again at full power but this time dimming moves the color point pretty much perpendicular to the Planckian locus and sharply towards the green area of the chart as well as increasing the CCT to about 7500 K. This much shift on the CIE chart is very significant and would likely be very objectionable. I should point out that these shifts would only be seen when running all three LEDs with the same linear dimming curve. I would hope and expect that any manufacturer using such a technique would be aware of this issue and would modify the dimming curves to help counteract this effect. **Figure 4** illustrates the results for these four combinations in more detail. The color points all start at much the same point at 100% but then shoot off in different directions as the LEDs are dimmed.

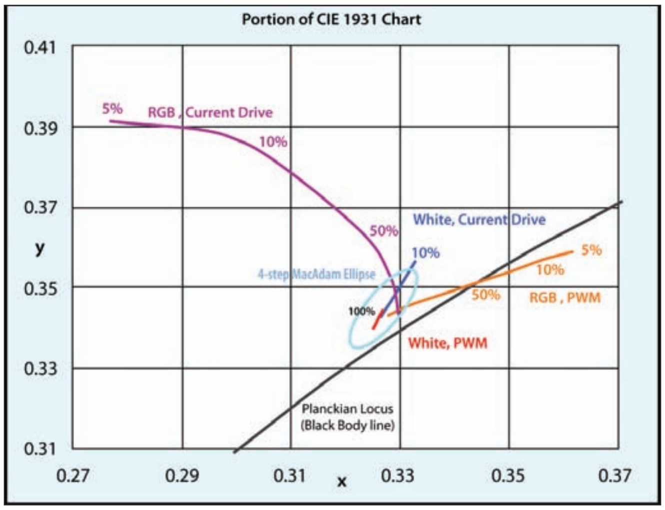



**Figure 4 – Dimming color shift for Phosphor White and RGB LEDs.**

These are worst case scenarios chosen for emphasis and, depending on how much the manufacturer of an LED fixture takes control of this situation and how much they leave up to the user; you may not see such extreme cases as illustrated here. However these shifts are all real and are something else we need to understand about using LEDs. If color consistency when dimming is important to you, then you need to look at the exact units you are planning to specify on a show using the control and dimming you are intending to use. The last LED fixture you used behaved in one manner when dimmed, but the chances are that another luminaire from a different manufacturer will behave differently. It isn't that one is right and the other is wrong—it's just a question of understanding the issues and knowing which is which.

*Thanks to the Lighting Research Center of the Rensselaer Polytechnic Institute, Troy, NY for permission to quote extracts from their research which was sponsored by the Alliance for Solid-State Illumination Systems and Technologies (ASSIST)* ■

**Mike Wood** is President of Mike Wood Consulting LLC which provides consulting support to companies within the entertainment industry on technology strategy, R&D, standards, and Intellectual Property. A 30-year veteran of the entertainment technology industry, Mike is the Treasurer and Immediate Past President of ESTA.

**Reference:**

1. Dyble, M, N. Narendran, A. Bierman, and T. Klein. 2005. *Impact of dimming white LEDs: Chromaticity shifts due to different dimming methods.* Fifth International Conference on Solid State Lighting, Proceedings of SPIE 5941, 291-299. Bellingham, WA: International Society of Optical Engineers.