# TITLE: PROGRAMMABLE MULTICHANNEL LIGHTING FOR ACCURATE SPECTRAL CONTROL OF DAYLIGHT EMULATION – SP07

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**Abstract:** Conventional lighting systems typically emit white light at a fixed correlated color temperature (CCT), but the spectral power distribution (SPD) underlying this output is often unspecified. While some systems allow CCT tuning or RGB-based chromaticity adjustment, these approaches still yield only one spectral solution for a given color point, limiting flexibility in reproducing complex spectral environments.

Spectrally programmable lighting systems overcome this limitation by incorporating multiple independently controllable spectral channels (e.g., 5, 8, or 24), enabling precise control over the emitted SPD. This allows for the generation of a wide range of spectra corresponding to the same CCT or chromaticity, making these systems particularly well-suited for simulating natural light sources—most notably, the highly variable SPD of daylight.

To inform the design of such lighting systems, we have conducted thousands of spectrometer measurements of daylight across a range of geographic locations and environmental conditions. This global dataset has been instrumental in guiding the development of both hardware and control algorithms. Applications of this technology include circadian lighting, sleep/wake studies, and imaging systems such as digital cameras and display devices

**Introduction:** The illuminated world around us is shaped primarily by two sources of light: natural daylight—produced by the sun and modified by the atmosphere—and artificial light generated by electricity. Over the past century, electric lighting has profoundly transformed human environments, largely in positive ways. In recent decades, lighting development has focused on improving energy efficiency, often quantified by lumens per watt (efficacy)[1]. Additional parameters such as correlated color temperature (CCT), color rendering index (CRI), total luminous output, and beam angle provide convenient single-number metrics for design and specification. However, these simplified measures reveal little about a light source's underlying spectral power distribution (SPD) or its temporal variability.

In contrast, daylight exhibits a complex and dynamic SPD that continuously evolves with time, atmospheric conditions, and solar position. Yet, when judged by conventional electric-light metrics, daylight often appears inconsistent or deficient—despite being the natural reference for human visual and biological systems. This paper examines the spectral and temporal dynamics of daylight compared with common electric light sources and demonstrates how modern multichannel electric lighting technologies can more faithfully replicate the qualities of natural daylight.

**Methodology:** Spectral data of light from various geographic locations and times of day were collected using both handheld and laboratory-grade spectrometers. The primary dataset used in this study was obtained with a AsenseTek Lighting Passport spectrometer, operated via an iPod interface that also enabled photographic documentation of each measurement site. Although this device is no longer commercially available, future field measurements will be conducted using a GL SPECTIS 1.0 Touch + Flicker spectrometer, which offers enhanced accuracy and temporal flicker analysis capabilities.

To reproduce and analyze the recorded spectra, Telelumen multichannel light player luminaires were employed to emulate the captured light distributions. The spectral output of these luminaires was subsequently verified and characterized using a laboratory-based Instrument Systems CAS 140D spectrometer, ensuring high spectral resolution and measurement precision.

**Results and Discussion:** Telelumen began conducting field recordings of daylight spectra in August 2015 during a trip to Sweden, with measurements taken in both Stockholm (southern Sweden) and Abisko, located above the Arctic Circle. Since then, additional recordings have been collected in over 90 cities across North America, Europe, and Asia, encompassing a broad range of seasons, times of day, and atmospheric conditions.

Most measurements were obtained in locations that reflect typical human environments—such as parks or open spaces with a clear north-sky view. However, some data were also collected under direct sunlight and in areas exhibiting visible atmospheric pollution, allowing for comparative analysis of diverse lighting conditions.

The spectrometers used for these recordings are equipped with cosine correctors, enabling the sensor to capture an average spectral power distribution representative of the entire visible sky hemisphere. This design approximates human visual experience, as people naturally move and shift gaze directions over time. In most cases, the spectrometer was held at a 45° angle relative to the ground to simulate a typical upward viewing orientation; deviations from this angle were noted in the data filenames.

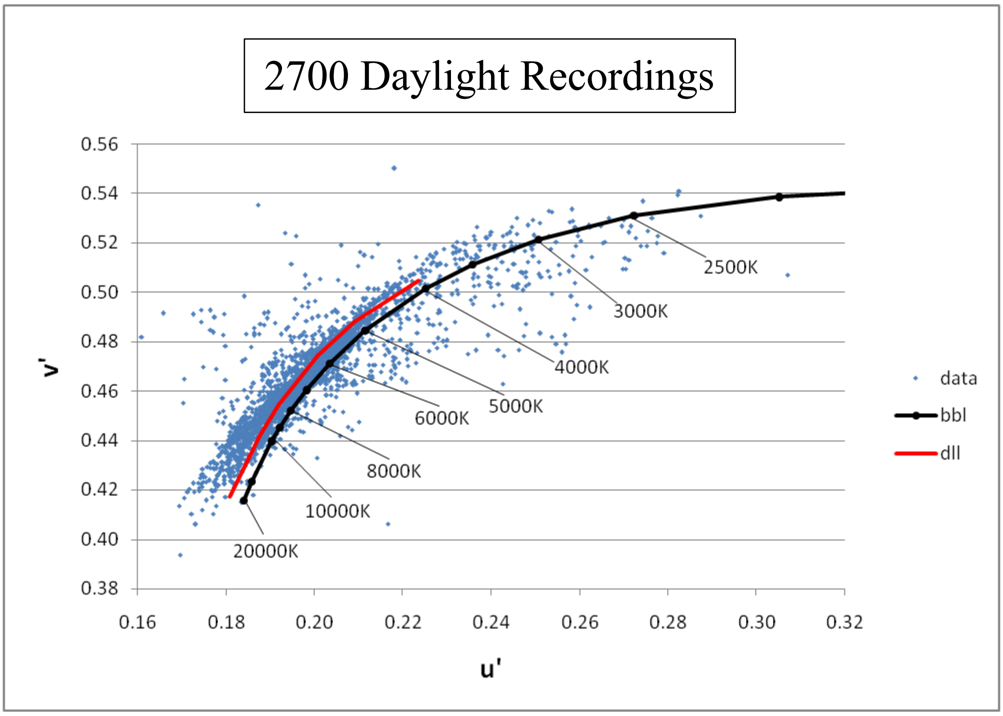

Figure 1.

Figure 1 summarizes the collected chromaticity data. The heavy black line represents Planck’s blackbody locus, a useful reference for understanding the range of light sources perceived as “white.” However, there is no direct physiological link between human visual perception and an ideal blackbody radiator. It also does not account for the influence of atmospheric scattering and absorption. The red line indicates the CIE-defined daylight locus, which attempts to model the average spectral modification of sunlight by the atmosphere. As shown in the figure, the measured data deviate substantially from this standardized daylight curve, highlighting the complex variability of real-world daylight conditions.

An additional observation is that daylight chromaticities predominantly correspond to correlated color temperatures (CCTs) above 4000 K, even during sunrise and sunset. Although the solar disk itself exhibits much lower apparent temperatures at these times, it constitutes only a small fraction of the total luminous environment and is uncomfortable to view directly.

In contrast, most electric light sources rarely exceed 4000 K due to design constraints driven by luminous efficacy. This emphasis on efficiency—weighted by the standard observer cone response shown in Figure 2—tends to limit the availability of higher-CCT lighting products. Consequently, electric lighting often fails to replicate the spectral richness and variability inherent in natural daylight.

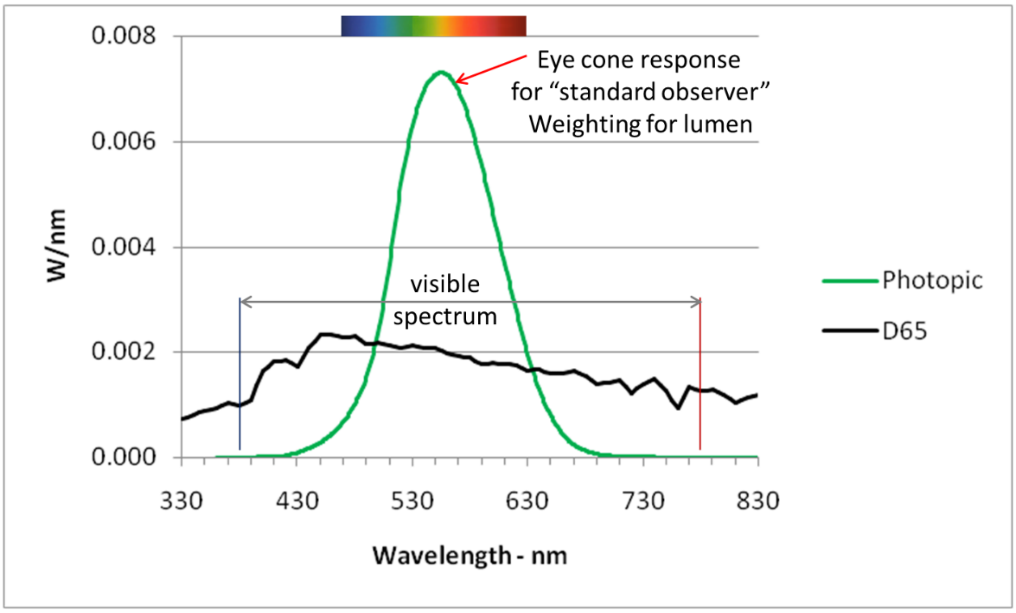

Figure 2.

As illustrated in Figure 2, the CIE Illuminant D65 serves as the most commonly referenced point on the daylight locus shown in Figure 1. Also depicted is a rainbow rectangle at the top of the figure, representing the typical spectral range of a digital display. In both electric lighting and display technologies, only about half of the visible spectrum is typically represented, leaving substantial spectral regions underrepresented compared to natural daylight.

A key finding from our experimental analysis concerns the general aversion to high-CCT (correlated color temperature) electric lighting. Empirical evidence suggests that this discomfort arises primarily from the absence of deep red spectral components—specifically wavelengths of 660 nm and longer. We hypothesize that this deficiency impacts the accurate rendering of human skin tones, as deep red wavelengths are critical for reproducing the color of oxygenated blood, a dominant influence in the perception of healthy skin[2]. Figures 3 and 4 provide visual context for this effect.

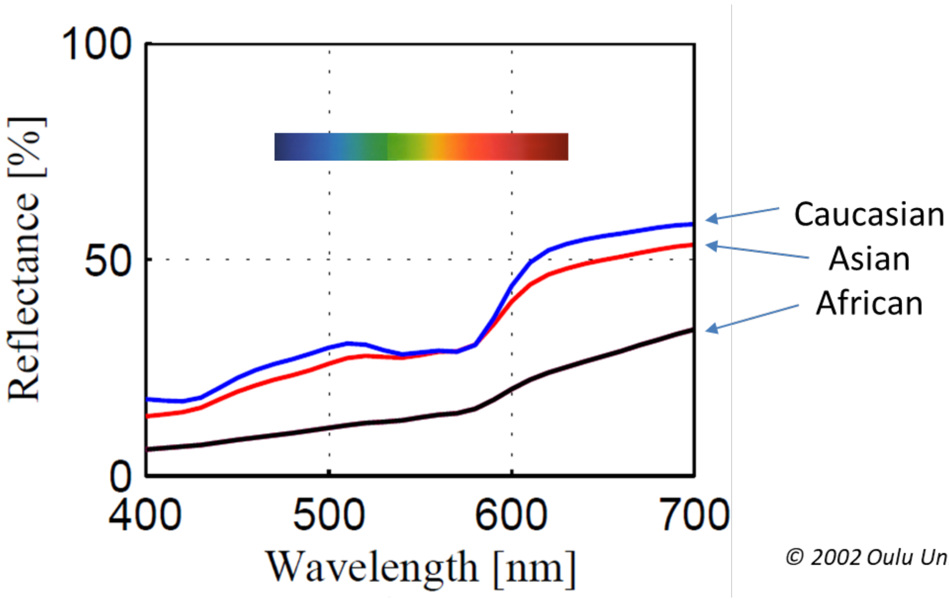

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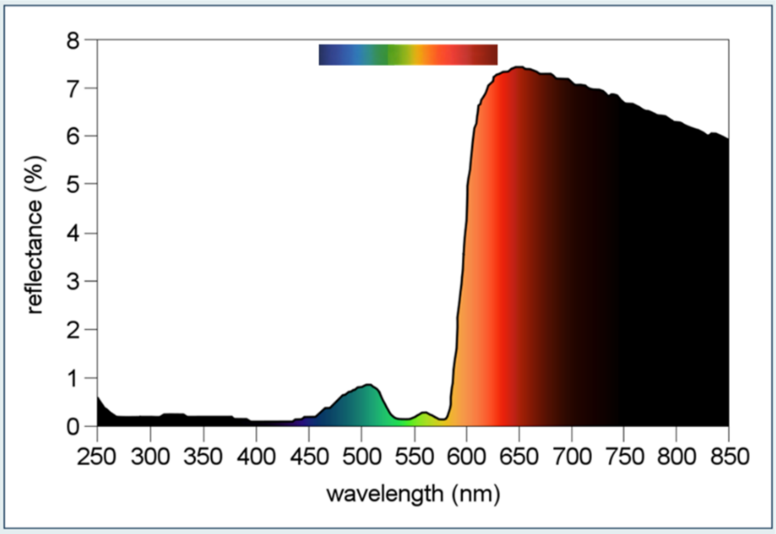
Figure 3.



Diffuse reflectance of human blood with a hematocrit of 33%, oxygen saturation of 100%, and mean cell volume of 83 femtoliters. Public Domain Image, data source: M. Meinke, image source: Christopher S. Baird.

Figure 4.

At the opposite end of the visible spectrum, violet light enriches visual experience by extending color differentiation beyond blue and by exciting optical brighteners commonly present in paper, textiles, and coatings. The inclusion of UVA radiation (around 365 nm)—commonly known as black light—can further enhance these effects by stimulating fluorescence in materials that respond to near-UV wavelengths.

Figures 5 and 6 present spectral power distribution (SPD) measurements of daylight recorded at two different locations, spanning periods from before sunrise to after sunset. Significant variations were observed in both SPD and CCT/chromaticity throughout the day. In Como, Italy, CCT values ranged from a low of 4,185K at 18:45 to a high of 25,127K at 21:10 (after sunset). Similarly, in Yosemite, California, CCT values fluctuated between 5,100K at 07:26 and 21,600K at 06:44 (shortly after sunrise). These results highlight the extreme dynamic range of natural daylight, underscoring the challenge for electric light sources to replicate its spectral and temporal variability.

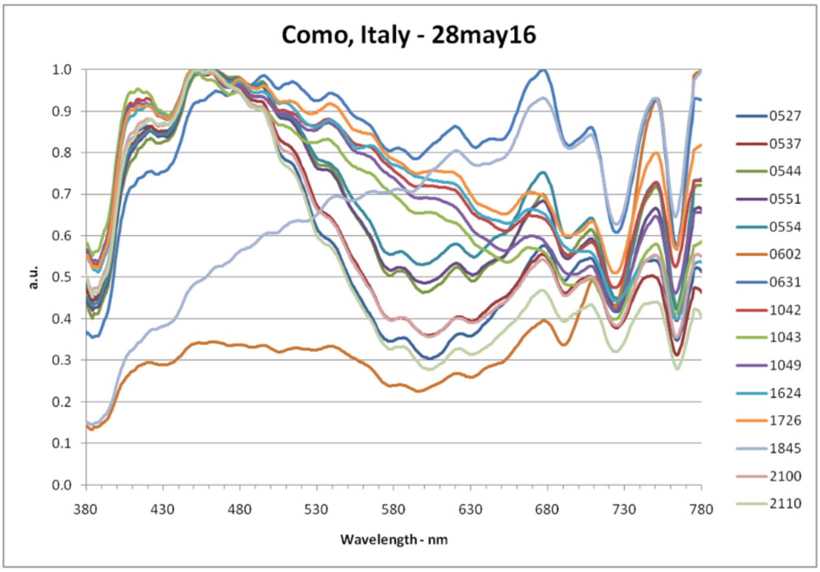


Figure 5.

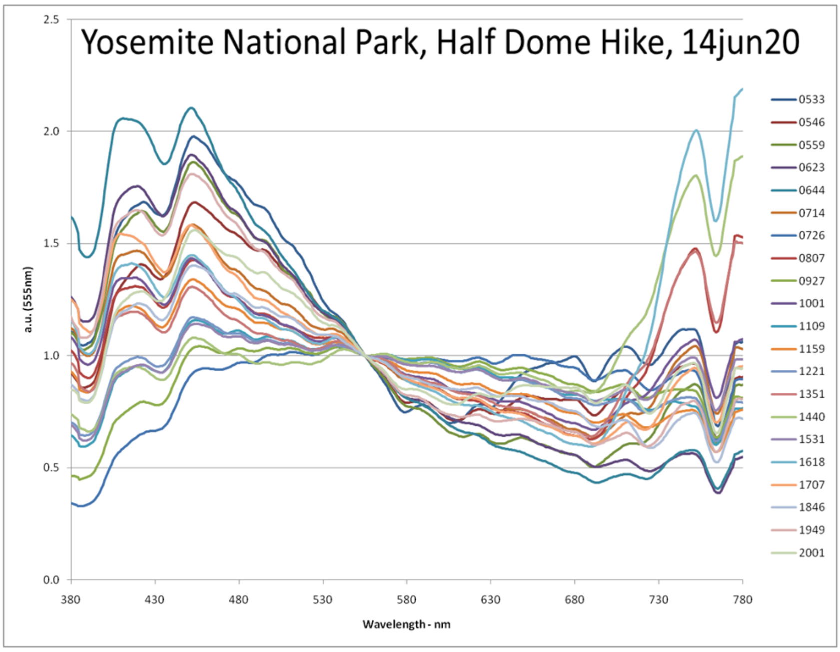


Figure 6.

Figure 7 illustrates the substantial variation in both spectral power distribution (SPD) and correlated color temperature (CCT), as well as their visible effects on object appearance—in this case, a human hand—depending on the direction of observation.

In the upper panel of Figure 7, the SPD of the eastern sky over Santorini Island, Greece, is shown near sunrise. The recorded CCT is 5,531K, while the hand is illuminated by light reflected from the western sky. Conversely, in the lower panel, the SPD of the western sky is presented, where the CCT measures 8,306K, and the hand is illuminated by light from the eastern sky.

Traditional interpretations of circadian-effective lighting typically describe sunrise and sunset as having low CCT values—around 2,700K—with midday light reaching higher CCTs near 6,500K. However, the data presented in Figure 7 challenge this conventional assumption. In practice, as demonstrated across numerous Telelumen field recordings, sky luminance and spectral characteristics often deviate significantly from the expected pattern, particularly during transitional times such as sunrise and sunset. These findings emphasize the complexity and directionality of natural daylight, suggesting that circadian lighting models based on simple CCT progression may inadequately represent real-world conditions.

Figure 7.

**Common Electric Light Sources:** As mentioned previously, most electric light sources do not emit a continuous visible spectrum. This limitation arises primarily from design optimizations focused on luminous efficacy, as represented by the familiar “bell curve” in Figure 2.

Exceptions include incandescent and halogen lamps—which have largely been regulated out of the market—and advanced multichannel systems that will be discussed later.

The following spectral power distribution (SPD) examples help illustrate this concept. Figure 8 shows the SPD of a 60W incandescent lamp, which emits across the entire visible spectrum, including deep red and violet wavelengths. In contrast, Figure 9 presents triband fluorescent lamps, which exhibit incomplete spectral coverage and distinct spikes corresponding to their phosphor emissions, and in particular, near the peak of the human visual response curve. Figures 11 and 12 show SPDs of white and RGB LED systems, respectively. Both lack the full visible spectrum, particularly the RGB configuration, although this design enables flexible color tuning for illumination and display applications.

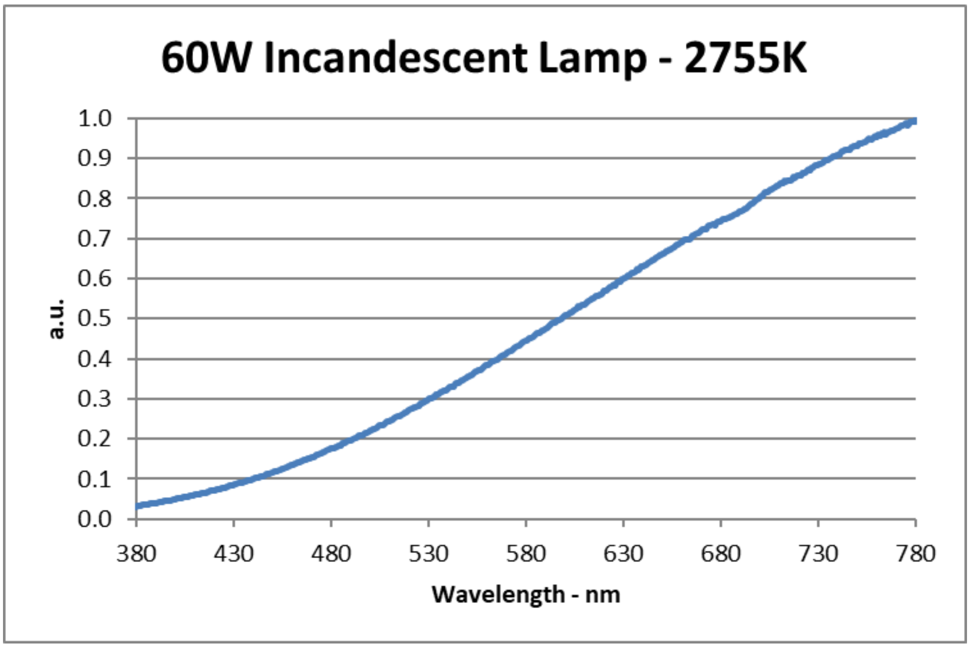


Figure 9.

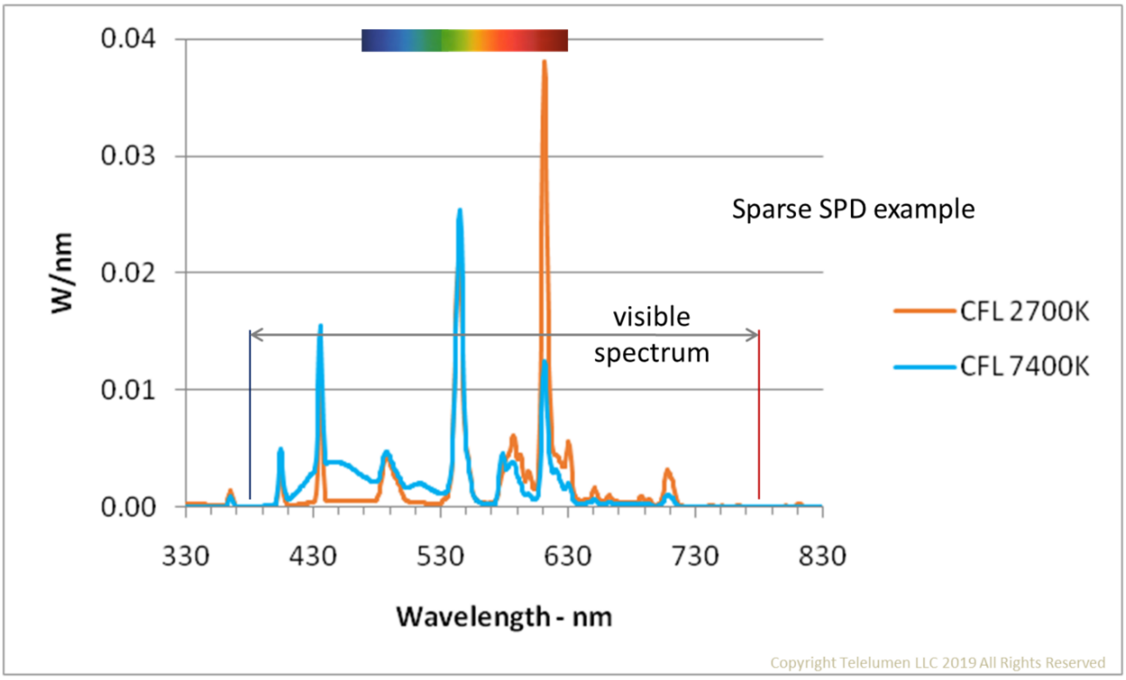


Figure 10.

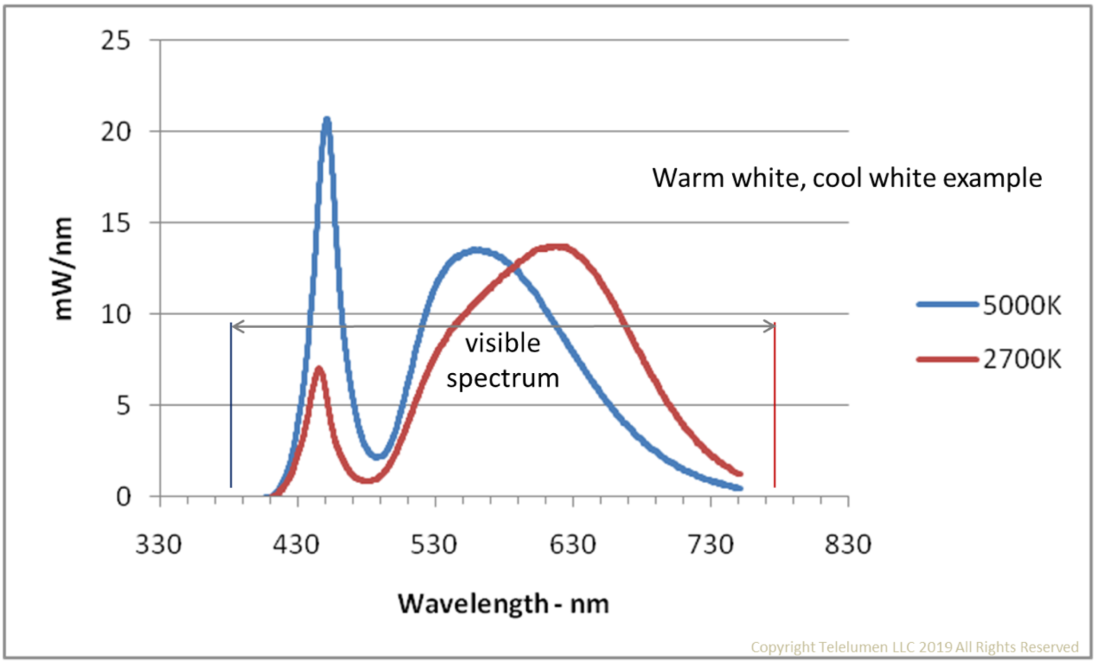


Figure 11.

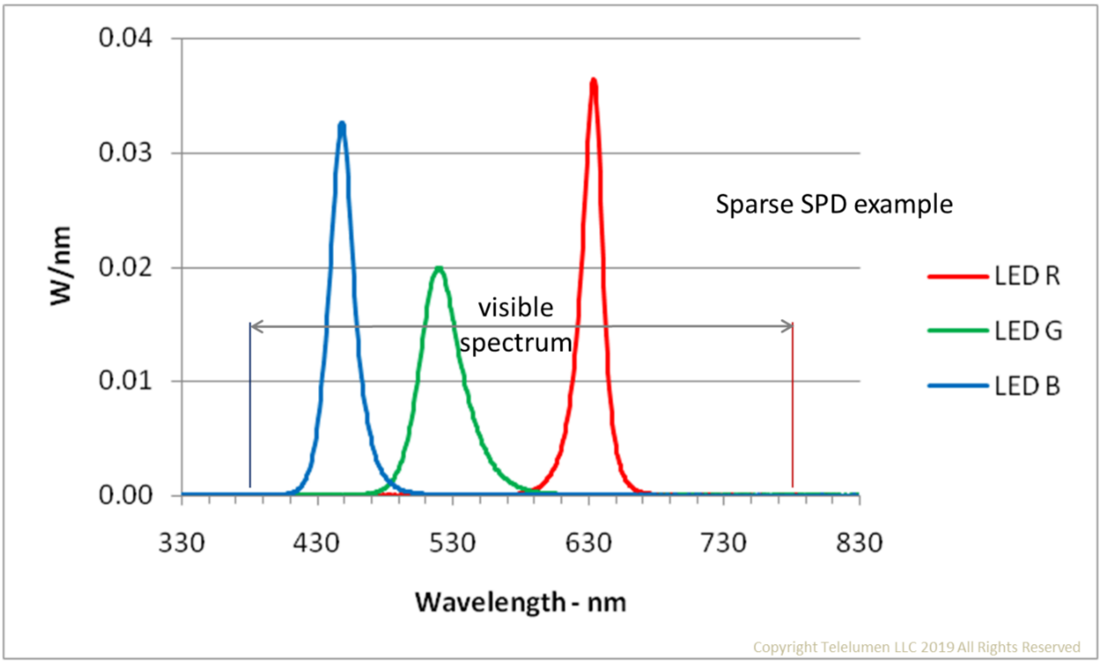


Figure 12.

As a general rule, light sources that humans find visually pleasant and biologically supportive are those with a broad visible spectrum—often extending into the ultraviolet-A (UVA) and near-infrared (NIR) regions. Examples include daylight, firelight, incandescent and halogen lamps, and modern high-channel programmable lighting systems.

**Multichannel Illumination:** The spectrum of a light source is typically determined either during manufacturing or, in advanced systems, can be subsequently programmed by the user. In the first category, the most common approach is to use high-energy photons—such as ultraviolet (UV), violet, or royal blue light—as excitation sources for one or more downconverters, including phosphors or quantum dots. This principle underlies the operation of both fluorescent lamps and white LEDs.

In the second category—tunable systems—the primary method involves combining red, green, and blue (RGB) emitters. Secondary approaches may include blending two or more fixed correlated color temperature (CCT) white sources and tuning between them, or adding a white or amber emitter to an RGB configuration. In the RGB case, any color that lies within the chromaticity triangle defined by the three primaries can be achieved through a specific geometric ratio of those primaries.

To enable true programmable spectral control, more than three primaries are required. The minimum number depends on the desired precision, spectral range, and cost constraints. For the purposes of this paper, five channels represent a reasonable minimum. At the high end, there is effectively no upper limit—the greater the number of independently controllable channels, the higher the achievable accuracy, albeit at increased cost and complexity.

Using more than three primaries introduces both opportunities and challenges. The opportunity lies in being able to produce multiple distinct spectral power distributions (SPDs) corresponding to the same chromaticity or CCT. For example the circadian[3] stimulus of a light source can be increased or decreased while holding the chromaticity constant. The challenge, however, is the vast number of possible SPD combinations for a given color point—far too many to adjust manually. Therefore, automated optimization is preferred. Algorithms employing cost functions can efficiently identify suitable solutions based on user-defined priorities, such as:

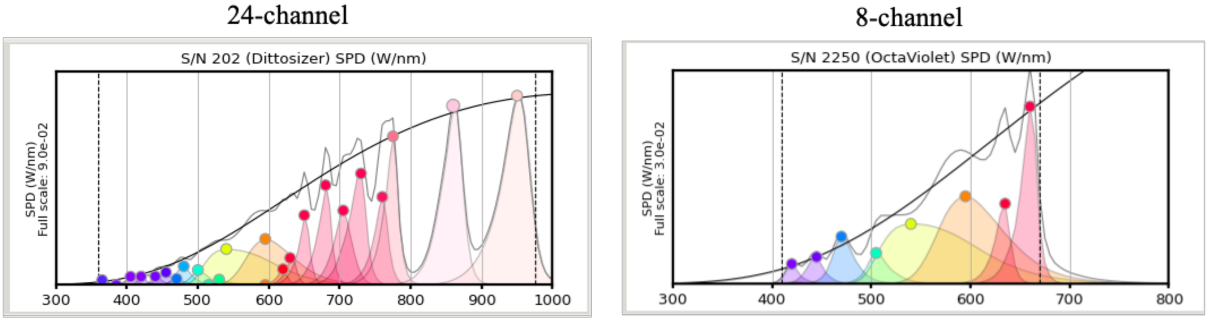
1. Matching a target spectrum with minimal error.
2. Matching the spectrum while correcting for chromaticity.
3. Optimizing for color rendering quality.
4. Minimizing energy consumption.

Another critical factor is the bit depth, or the number of intensity levels from zero to full output. Entry-level systems typically use 8-bit control, offering 256 levels per channel. This results in the frequently advertised "16.7 million colors" for entry level RGB systems ($2^{8+8+8} = 16{,}777{,}216$). While impressive in marketing, 8-bit resolution is insufficient for high-quality illumination or many display applications. For instance, the first incremental step above zero in an 8-bit system is roughly 0.5% of the total dynamic range, whereas the human visual system—especially under low light conditions—can detect changes as small as 0.0001%. Achieving this sensitivity would require 20-bit control, which is generally impractical. A more feasible compromise is 12-bit control, providing 0.02% resolution per step, though this adds cost beyond 8-bit systems.

Two primary methods are used to achieve fine gradations in light output: pulse-width modulation (PWM), which controls the on-time within each cycle, and amplitude modulation (AM), which regulates the current through the source. These techniques can also be combined—much like adjusting both aperture and shutter speed in photography—to achieve high dynamic range and precision.

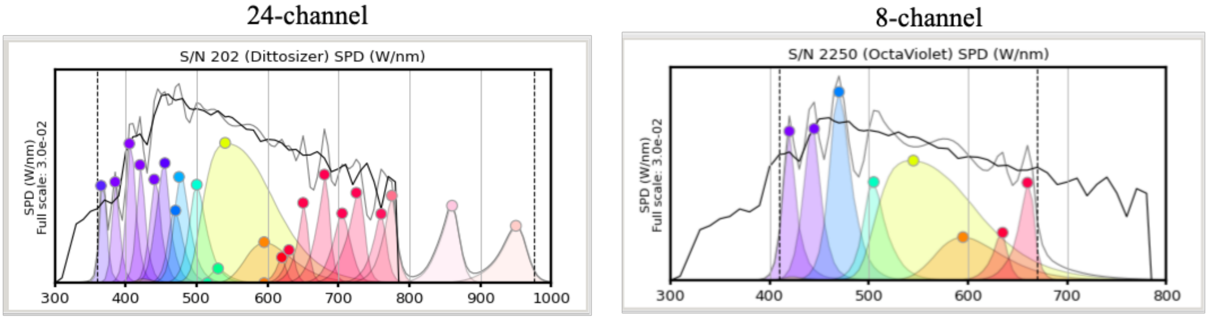
Additional desirable characteristics of light sources extend beyond spectral quality. These include temporal behavior, beam pattern, and directionality. Natural light sources such as daylight and fire exhibit rhythmic temporal variations that contribute to their visual comfort experience. Daylight also provides a combination of direct (collimated) sunlight and diffuse skylight, producing a balanced visual environment. Advanced electric lighting systems can replicate both effects within a single space. Furthermore, daylight's processional motion—the shifting of shadows throughout the day—adds dynamic visual interest, a quality that can also be simulated in theatrical and architectural lighting systems.

This paper focuses on achieving accurate and dynamic spectral control over time. Figures that follow illustrate examples from 8-channel and 24-channel systems. While temporal changes are difficult to depict on paper, these systems can alter their spectra on a millisecond timescale, enabling real-time spectral adaptation. The following examples demonstrate spectral matching capabilities of both configurations.


24-channel

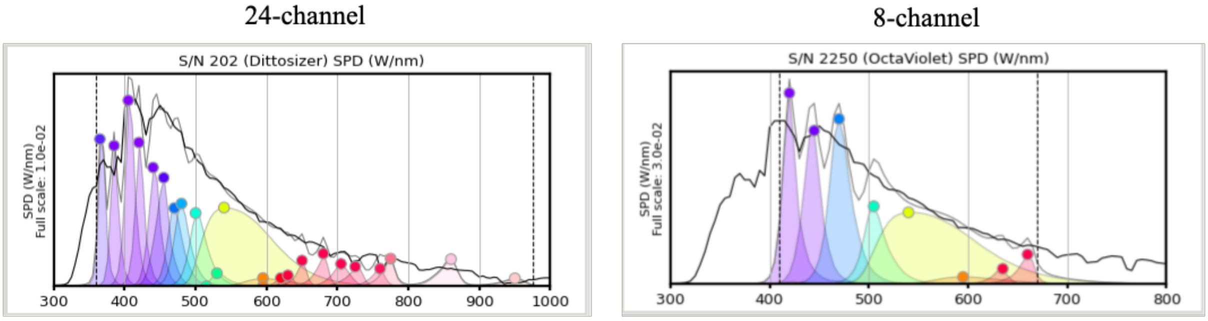
8-channel

2755K Incandescent Target


24-channel

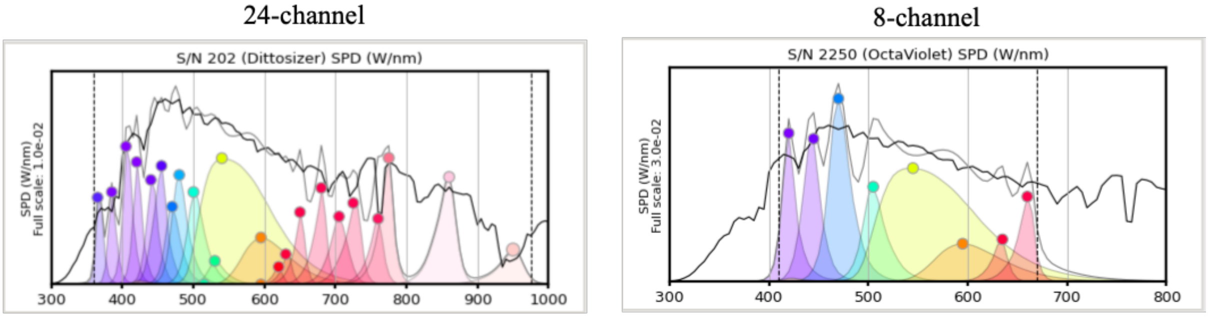
8-channel

6500K Daylight Target


24-channel

8-channel

Daylight Recorded at 1712, 18440K


24-channel

8-channel

Daylight Recorded at 1714, 6657K

Figure 13.

Figure 13 shows spectral matches for four different SPDs using both 8-channel and 24-channel systems. The heavy black line represents the target SPD, while the lighter gray line indicates the matched output. The colors represent the individual channels in their relative proportions to make up the final SPD (gray line). The upper two examples correspond to spectra from Figures 2 and 9. The lower two sets are random daylight recordings captured a few minutes apart while observing different areas of the sky. Note the significant variation in these SPDs, which is rarely accounted for in standard daylight reference models.

**Future Work:** The spectrometer recordings discussed in this paper were obtained using a cosine corrector, which captures an averaged representation of the sky's spectrum. We have since acquired a Specim IQ hyperspectral camera to obtain more spatially detailed measurements, allowing us to map how spectral power distribution varies across different regions of the sky. This capability will enable deeper analysis of natural light variability and inform more accurate daylight replication strategies.

**Conclusion:** There are many available options for illumination, but daylight remains the ideal light source for humans and other living organisms. We evolved under its dynamic spectrum, and it is reasonable to assume that our physiology and behavior have adapted to either harness or protect against its energy as needed. Spectrometer measurements reveal that daylight exhibits far greater spectral variability than is typically recognized—varying with geographic location, time of day, season, atmospheric conditions, and even the direction of gaze.

In contrast, most electric light sources bear little resemblance to daylight. Their SPDs are generally static and optimized primarily for luminous efficacy, not for biological or perceptual quality. Regulatory standards have reinforced this by emphasizing efficiency in terms of perceived brightness rather than total spectral output. A shift toward efficiency metrics—such as optical watts output per electrical watt input, or photons emitted per watt—would allow more of the visible spectrum to be utilized, opening opportunities for true daylight replication in artificial lighting.

Simplified descriptors such as correlated color temperature (CCT) or chromaticity are inadequate for capturing the richness and complexity of daylight. The spectral power distribution (SPD) of a light source fundamentally determines how objects appear and how light influences human physiology. To the extent that accurate visual rendering, comfort, and biological impact are important to a given application, the spectral information and findings presented in this paper should be taken into careful consideration.

**References:**

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